# Appendix G: Field Testing and Evaluation of WAVE/DSRC Communications Functionalities

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# 1 OVERVIEW

## 1.1 Goals

The overall goal of the activities described in this appendix was to test and evaluate communications functionalities for potential vehicle safety implementations, in order to continue pre-competitive research into the feasibility of using 5.9 GHz DSRC to enable and enhance vehicle safety systems and applications. Throughout this testing, the main focus was on evaluating communications data necessary to establish feasibility and to enable the future design and development of two potential vehicle safety applications – traffic signal violation warning and emergency electronic brake lights. Communication scenarios were developed that would support early prototype vehicle safety applications in order to evaluate communications requirements. As used herein, communication scenarios include transmissions between a roadside unit (RSU) and an on-board unit (OBU), as well as OBU-to-OBU, relevant to potential safety applications in real-world environments. The activities focused on data collection and analysis in preparation for the full functionality prototype development of prospective vehicle safety applications.

For the RSU to OBU case, the goal within this task was to work towards implementation requirements for interfacing with existing infrastructure traffic control equipment to effectively establish vehicle safety applications. Part of this work consisted of cooperation with local road authorities to understand the hurdles of an installed, safety-specific test RSU as required for the traffic signal violation warning prototype application scenario. In addition, arrangements were made to send test data from roadside locations in real-world intersection locations using a programmed controller box.

For the OBU to OBU case, the major focus was on the implementation of the standard vehicle message set being developed by SAE to support vehicle-to-vehicle safety applications such as emergency electronic brake lights. A test plan was developed and conducted for both test track and public roadway environments. The goal of the testing in this portion of the task was to evaluate available DSRC standards for communications reliability, update rate, and range under vehicle-to-vehicle operations.

The collected data under Task 10 served two purposes:

- To begin to assess the viability of DSRC communications in real-world conditions.
- To provide raw data as a basis for potential future safety application algorithm development in a simulation environment.

## 1.2 Test Plan

Three types of testing were identified as requiring additional attention above and beyond that testing accomplished within the scope of Task 4:

- **Transmission Characteristics at Intersections –** Although some Task 4 testing took place in public road settings, a great deal of the testing was conducted at test track facilities, and no specific efforts were aimed at identifying troublesome/unique intersections or determining expected performance at these junctures.

- **Intersection Controller Data Exchange –** Task 3 identified theoretical information that might be sent from an intersection controller, but no actual controller broadcast tests had been attempted during Task 4 testing due to hardware constraints. Investigating the hurdles of such information exchange was seen as crucial to enable future application development.

- **Vehicle Data Exchange –** Task 4 provided extensive vehicle-to-vehicle testing, but the packets consisted mostly of random filler, and provided no instantaneous information from the vehicle's electrical architecture and sensors. Proving the ability to exchange such information between manufacturers was seen as crucial to enable future application development.

### *1.2.1 Transmission Characteristics at Intersections*

Various intersections in the Detroit and San Francisco Bay areas were selected for their unique characteristics in order to gain a better understanding of how these variations affect DSRC communications. For the sake of expediency, the Task 4 Communication Test Kits (CTKs) and the Task 6C antennas were used as an improvised roadside unit, with a few modifications to the antenna mounting arrangement. Though the Task 6C antennas were designed for vehicle mounting, their omni-directional functionality was deemed to be desirable for determining the general transmission characteristics of a CTK broadcasting from one of the corners at each selected intersection. The investigation focused on plotting the relative received signal strength of transmissions sent from the stationary RSU and received on portable test equipment carried in a moving vehicle.

A number of intersections in both the Palo Alto and Detroit teams were evaluated using the improvised RSU equipment. The specific intersections evaluated covered a broad range of roadway geometries, structural/terrain occlusions, and traffic environments. The pages that follow (Tables 1-8) identify the selected intersections and describe the features that are of particular interest. The findings from these evaluations are presented in Section 2 of this appendix.

| Location | Setting/Traffic | Configuration | Obstructions | Illustration |
|---|---|---|---|---|
| Oakwood Boulevard & Michigan Avenue<br><br>Dearborn, MI | Urban area normally experiences heavy daytime traffic | 2 lanes in each direction and a center lane for left turns at the intersection<br><br>Oakwood Blvd rises to the north and crests a small hill. It descends to the south, bending out of sight around a corner | Densely packed buildings and tree-lined sidewalks<br><br>A concrete buttressed railroad overpass to the south on Oakwood Blvd |  |
| Crooks Road & Big Beaver Road<br><br>Troy, MI | Urban area continually full of moving traffic during the daytime hours | 3 lanes each way eastbound and westbound on Big Beaver Road, separated by medial strip<br><br>Fewer lanes of traffic in the north and southbound directions on Crooks Road | Buildings nearby (a few with 10 floors or more), but the buildings are far removed by large parking lots<br><br>Small trees and bushes on the media strip |  |

**Table 1. Oakwood/Michigan and Crooks/Big Beaver Intersection**

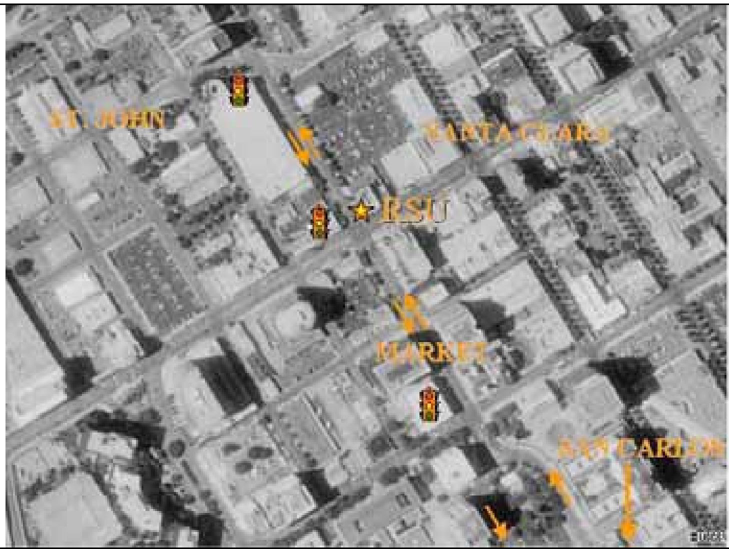
| Location | Setting/Traffic | Configuration | Obstructions | Illustration |
|---|---|---|---|---|
| Santa Clara Street & Market Street<br><br>San Jose, CA | Urban area with heavy traffic during the time of the testing | 2 lanes in each direction and a center lane for left-turns at the intersection. | There are closely packed high rises and trees along both sides of Market Street. |  |
| Hillview Avenue & Hanover Street<br><br>Palo Alto, CA | Urban area with light traffic during daytime | Both Hillview and Hanover have a single lane in both directions and a center lane for left-turns at the intersection | The north end of Hanover is slightly uphill and the south end has a 90-degree bend to the west |  |

**Table 2. Santa Clara/Market and Hillview/Hanover Intersection**

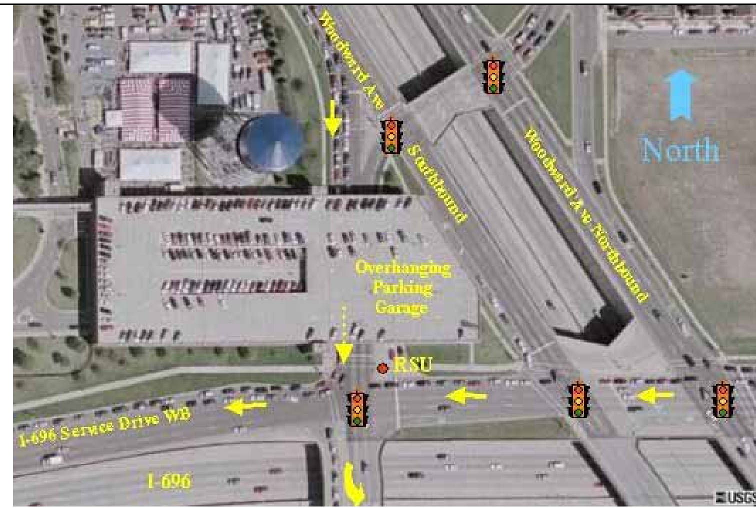
| Location | Setting/Traffic | Configuration | Obstructions | Illustration |
|---|---|---|---|---|
| Woodward Avenue & I-696 Service Drive<br><br>Huntington Woods, MI | Urban area with medium to heavy traffic during the day | 4 lanes in the southbound direction and 5 lanes in the westbound direction, both include a left turn lane | Line of sight on southbound Woodward is blocked by terrain and trees along the curve in the road<br><br>Vehicles pass beneath an overhanging parking garage just before the intersection |   |
| El Camino Real & 5th Avenue<br><br>Atherton, CA | Suburban area with medium traffic during the time of the testing | El Camino has three lanes for each direction and two additional lanes for left-turning onto 5th<br><br>5th has two lanes for each direction and one left turn lane for southbound El Camino | A moderate amount of trees and buildings are along both sides of El Camino and the south-end is slightly curved |   |

**Table 3. Woodward/I-696 Service Drive and El Camino Real/5th Avenue Intersection**

| Location | Setting/Traffic | Configuration | Obstructions | Illustration |
|---|---|---|---|---|
| Woodside Road & Churchill Avenue<br><br>Redwood City, CA | Suburban area with medium traffic during the daytime | Woodside has two lanes in both directions and Churchill has one in both directions<br><br>Woodside has a left turn lane with a traffic light at the Churchill intersection | There are plenty of trees along both sides of Woodside<br><br>Both directions on Woodside away from the intersection have uphill slopes, and the south end is slightly curved to the west |  |
| Country Club Drive & 12 Mile Road<br><br>Farmington Hills, MI | Suburban area with light to heavy traffic conditions depending on the time of day | Eastbound 12 Mile has 2 lanes and a right turn lane. Westbound 12 Mile has 2 lanes and a left turn lane<br><br>Country Club Drive has 2 lanes in each direction separated by a median strip | Country Club Drive has an obstructed line of sight to the RSU due to several trees<br><br>Vehicles traveling East on 12 Mile Road also have obstructed line of sight due to trees |  |

**Table 4. Woodside/Churchill and Country Club/12 Mile Intersection**

| Location | Setting/Traffic | Configuration | Obstructions | Illustration |
|---|---|---|---|---|
| Auburn Road & Squirrel Road<br><br>West Bloomfield, MI | Suburban area with light traffic during the time of testing | Auburn Road has two lanes in each direction<br><br>Squirrel Road has 1 lane in each direction and a center left turn lane | Squirrel Road curves suddenly just north of the intersection and the line of sight is blocked by terrain along the curving roadway |  |
| Sand Hill Road & Whiskey Hill Road<br><br>Menlo Park, CA | Suburban area with medium traffic conditions.<br><br>Sand Hill runs relatively north-south, and Whiskey Hill intersects Sand Hill at an angle, coming from the north-east | There is a triangle-shaped median with stop sign in the middle of the intersection, separating Sand Hill from two branches of traffic that move southbound on Whiskey Hill | There are a number of tall trees and shrubs<br><br>There are up-hill grades in both directions on Sand Hill going away from the intersection |  |

**Table 5. Auburn/Squirrel and Sand Hill/Whiskey Hill Intersection**

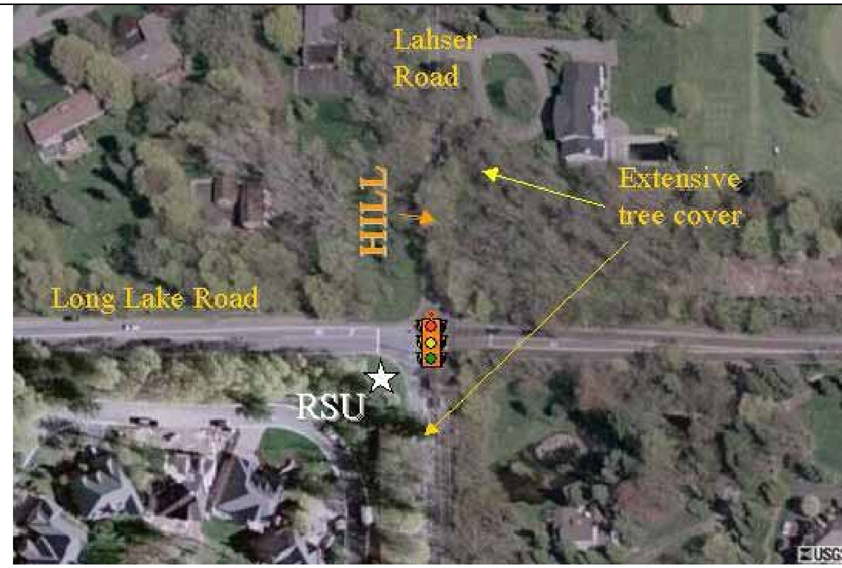
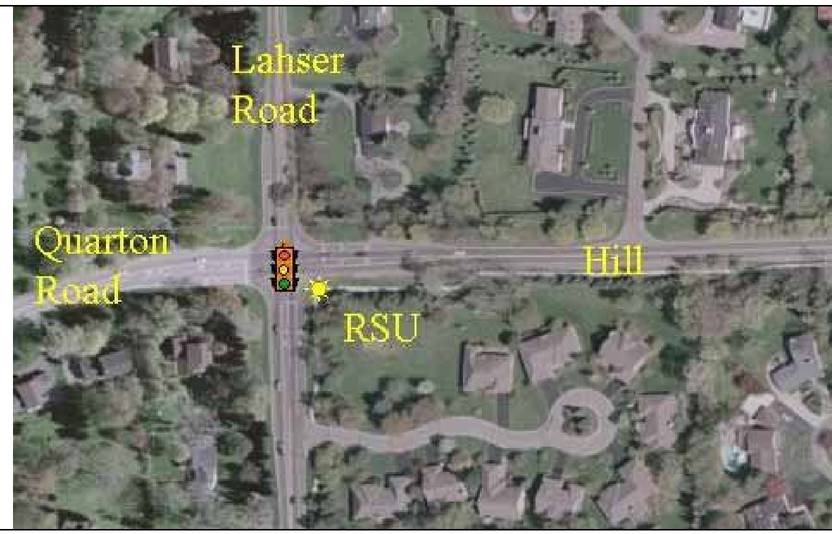
| Location | Setting/Traffic | Configuration | Obstructions | Illustration |
|---|---|---|---|---|
| Long Lake Road & Lahser Road<br><br>Bloomfield Hills, MI | Suburban area.<br><br>Long Lake Road has a steady amount of residential traffic during the daytime hours<br><br>Lahser Road has slower, sparser traffic than Long Lake Road | Long Lake Road has two lanes of traffic in the east and westbound directions<br><br>North and southbound Lahser Road has one lane of traffic in both directions | Trees and bushes encircle the intersection and block line-of-sight in at least one, if not all, directions<br><br>A hill north of the intersection prevents line-of-sight to the traffic light until about 150m from the intersection |  |
| Quarton Road & Lahser Road<br><br>Auburn Hills, MI | Suburban area with medium traffic during the time of testing | Aside from left and right turn lanes at the intersection, these roads are limited to one lane of traffic in either direction | Considerable foliage close to the shoulder of the roads<br><br>Quarton rises to a hill about 200m to the east, and to the west, the road bends, disappearing from view within ~100m |  |

**Table 6. Long Lake/Lahser and Quarton/Lahser Intersection**

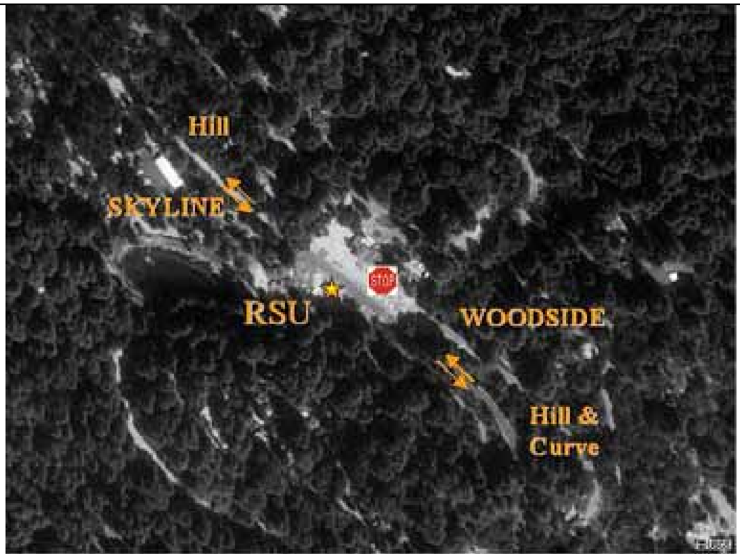
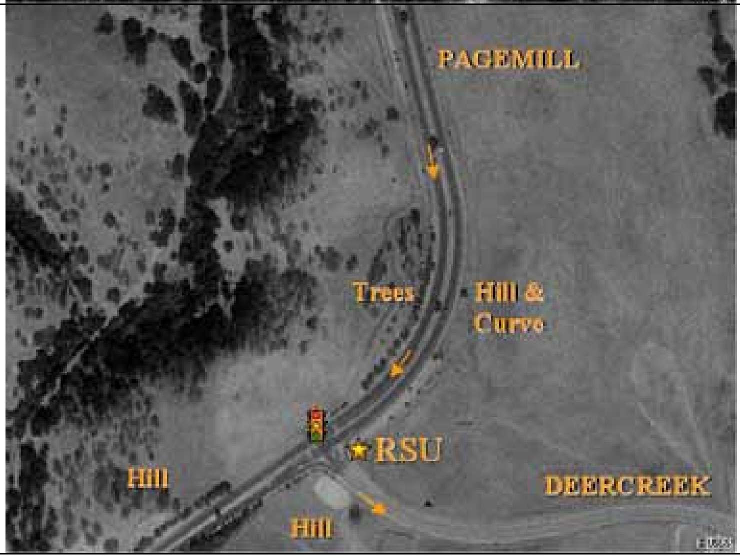
| Location | Setting/Traffic | Configuration | Obstructions | Illustration |
|---|---|---|---|---|
| Skyline Boulevard & Woodside Road<br><br>Redwood City, CA | Suburban area with light traffic during the daytime | Both Skyline and Woodside have a single lane in both directions<br><br>There are stop signs on Woodside at the intersection, but none on Skyline | Both directions on Skyline have uphill slopes and the southeastern end gradually curves to the south.<br><br>Dense foliage throughout the area and surrounding the intersection. |  |
| Page Mill Road & Deer Creek Road<br><br>Palo Alto, CA | Rural area with medium traffic during the daytime | Both roads have two lanes in both directions<br><br>Page Mill has a left turn lane with a traffic light at the Deer Creek intersection | Southbound Page Mill Road curves slowly toward the southwestern direction and goes uphill<br><br>There are trees along the curve of Page Mill Road |  |

**Table 7. Skyline/Woodside and Page Mill/Deer Creek Intersection**

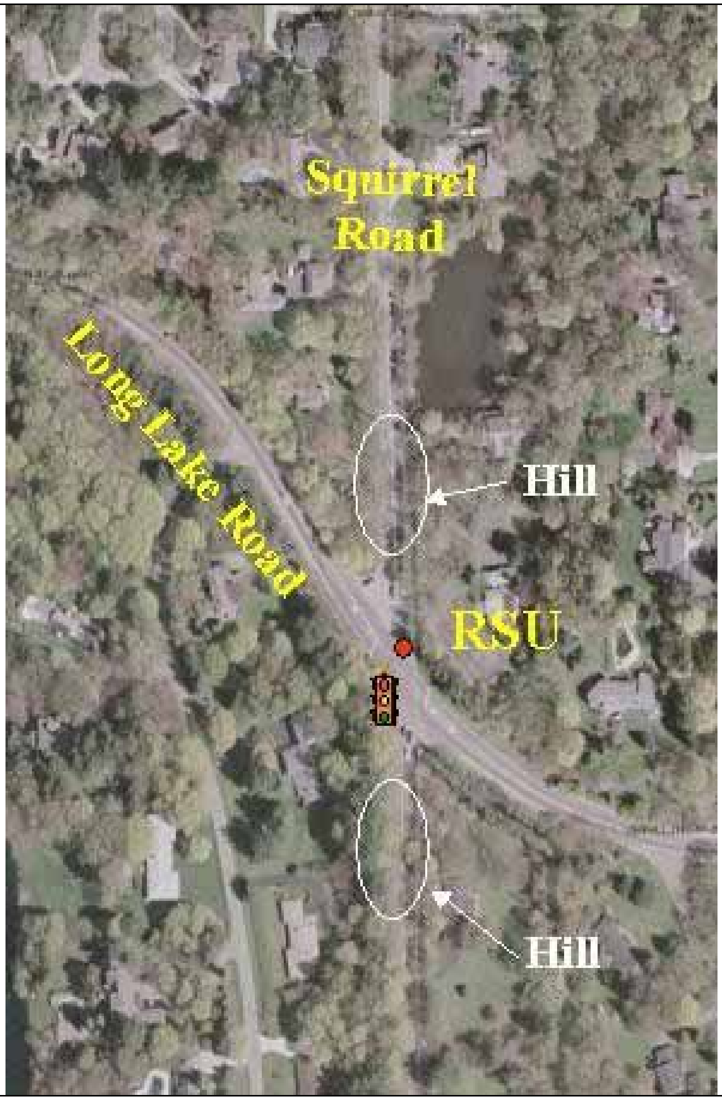
| Location | Setting/Traffic | Configuration | Obstructions | Illustration |
|---|---|---|---|---|
| Squirrel Road & Long Lake Road<br><br>Bloomfield Hills, MI | Suburban area with light traffic during the time of the testing | 1 lane in either direction for both roads, with left and right turn lanes at the intersection to accommodate the extreme curves of Long Lake Road | Squirrel Road has overhead foliage, as well as hills, both of which descend in the southbound direction<br><br>Long Lake Road has terrain and foliage along the curving roadway that eventually blocks the direct line of sight to the intersection |  |

**Table 8. Squirrel & Long Lake Intersection**

### *1.2.2 Intersection Controller Data Exchange*

After identifying applications in Task 3 that would utilize information sent from an intersection controller, a feasibility study covering this type of information exchange was seen as crucial to enable future application development. The Task 9 testing system was designed to interface with such a controller for this purpose. Rather than connecting the test equipment to a traffic signal controller that actually controls traffic lights, it was decided that it should be connected to a second controller to be purchased by the VSCC. This second controller could be programmed with exactly the same timing as the actual controller, eliminating any risk of inadvertent interference.

The choice of which signalized intersection to run the tests could be based on factors such as the previous establishment of a cooperative atmosphere between the VSCC and the Road Commission of Oakland County (RCOC), and also the elimination of those locations where the dynamic control of the traffic lights changes the signal timing. Testing at such an intersection would add another dimension of complexity that was beyond the scope of this preliminary feasibility study. The intersection chosen for the test was Orchard Lake Road and 10 Mile Road in Farmington, Michigan (Figure 1). The traffic signal controller shown in the inset of Figure 1 was programmed by the RCOC to use exactly the same timing as the controller at the selected intersection.


**Figure 1. Controller Test Site at Orchard Lake Road and 10 Mile Road**

The following tests were chosen for the traffic controller investigation:

- **Communication Performance Assessment:** A test to assess the communication performance at the intersection by comparing the amount of packets received with the amount of those sent

- **Traffic Signal Status Plot:** Plotting the instantaneous traffic status with respect to the location where the moving test vehicle receives the data

- **Reduced Power Transmit Testing:** A set of tests to investigate transmission power control by running successive trials at power levels of 12, 6, and 3 dBm

- **Vehicle-Vehicle and Vehicle-Infrastructure Testing:** An analysis that considers whether communications can be established and maintained between two OBU vehicles traveling on perpendicular legs of an intersection with a relatively low building density in the near vicinity

Section 3 of this report describes the results of these investigations.

### *1.2.3 Vehicle Data Exchange*

Several vehicle-to-vehicle communication tests were conducted to evaluate the WAVE Radio Modules (WRMs) that were developed in Task 6D. This testing would also feature the wireless exchange of CAN data between different vehicle makes. In order to vary the circumstances of the evaluation, the locations chosen for testing included the Milford Proving Grounds, the I-96 freeway, and the M-5 ramp to Twelve Mile Road, all in Michigan.

At the beginning of the Task 10 activity, it was noted that interfacing between the DSRC test equipment and an on-vehicle CAN bus could most readily be achieved by leveraging prior work completed within the CAMP project. It was determined that testing could be conducted using a Jaguar XKR developed by Ford for the EDMap project, and two Buick LeSabres developed by GM for the ACAS project. Other vehicles (all shown in Figure 2) would participate in a number of the tests and be capable of receiving the CAN vehicle signals broadcasted over the DSRC Control Channel. The following tests were selected for this phase of the vehicle-to-vehicle communications evaluation:

- **Test for Omni-Directional Coverage:** One test vehicle travels in a circle around a second vehicle to verify 360º coverage and overall signal reception.

- **Lead Vehicle Brake Test:** A braking test for two vehicles traveling in the same direction, intended to clarify the potential of DSRC to prevent rear-end collisions.

- **Test for Maximum Vehicle Range:** A slow-moving test to determine the maximum communication ranges and to identify if there are null zones for vehicle-to-vehicle communications.

- **Test for Communication Performance Under High Vehicle Speed:** A test to determine if there is degradation in communication performance under high relative speed conditions (70 mph for vehicles traveling in opposite directions).

- **Test for Communication Range Under Low Transmit Power:** A test to determine the reduction in communication range under low Transmit Power conditions.

- **Test for Communication Performance Under High Data Rate:** a test to determine the degradation in communication performance under high Data Rate transmissions (increased from 6 to 27 Mbps).

- **Vehicle-to-Vehicle Communications Testing:** A series of tests conducted on the I-96 freeway and the M-5 ramp in Michigan in order to evaluate communications performance on freeways

The results of these tests are described in Section 4 of this appendix.

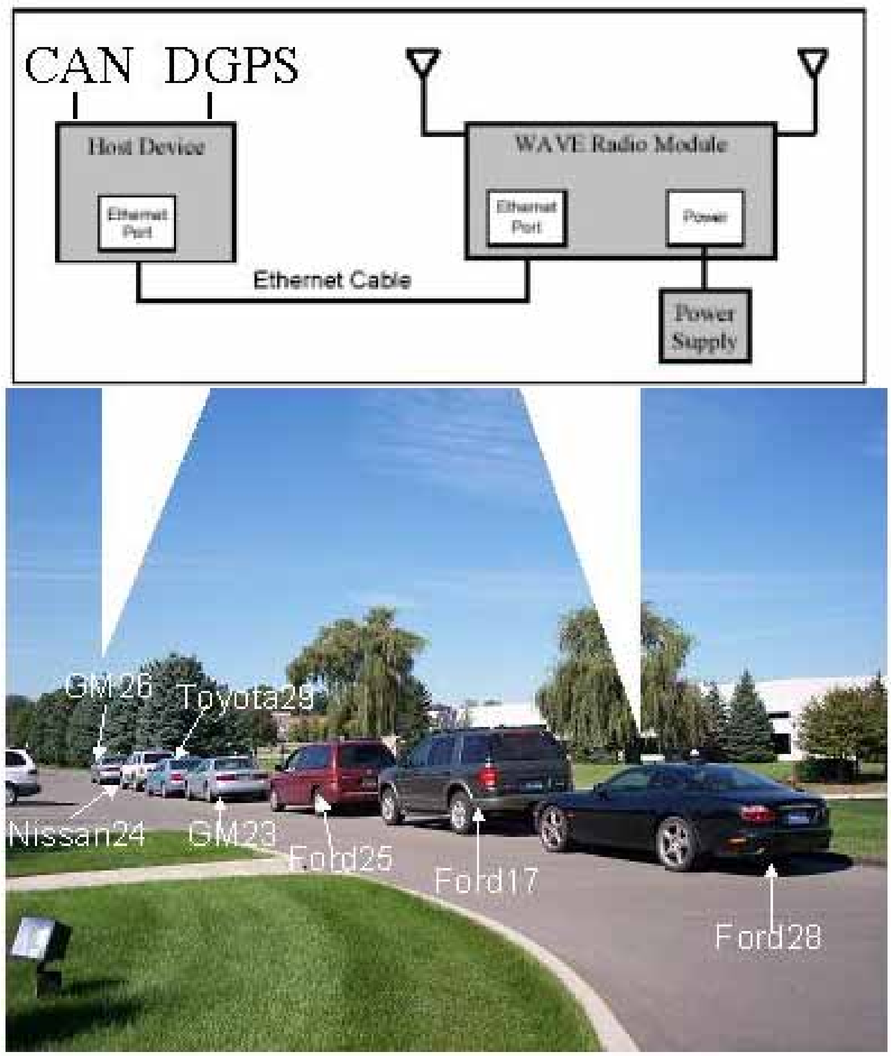



**Figure 2. Seven Vehicle Caravan with CAN Connectivity Highlighted**

# 2 TEST RESULTS FOR INTERSECTIONS

The Task 10 field-testing program was carried out for the most part on public roadways, with some baseline studies and equipment verifications conducted using the test track facilities at GM's Milford Proving Grounds. All intersection testing with portable equipment placed near the edge of each thoroughfare was conducted with prior approval from the public jurisdictions that were responsible for the intersections. The testing followed the planning set forth in Section 1.2 of this report, with the intention of investigating several remaining issues that were not covered within the Task 4 test scope.

## 2.1 Intersection Testing

In determining the appropriate equipment needed to carry out the Task 10 intersection tests, the antennas developed by M/A-COM during the Task 6C effort were applied to a test setup that satisfied potential height and placement characteristics of a DSRC roadside unit (RSU). In order to satisfy the objectives of the Task 10 testing, improvised RSUs were assembled as illustrated in Figures 3-6.

The Task 6C antenna was inverted and suspended approximately 10 feet above the roadside by means of a cross member attached to telescoping poles anchored into a heavy base plate. Transmitting both outward and towards the ground, the elevated antenna was basically mounted upside down in order to cover nearly the same vehicle-accessible area that the antenna normally would if mounted on an automobile.

- For the testing conducted in the Detroit area, the M/A-COM roof mount units were selected, which required the addition of a 1m diameter metalized foam disk to provide the ground plane necessary to produce the proper antenna radiation pattern.

- For the testing conducted in the Palo Alto area, the M/A-COM mirror mount units were utilized, which did not require a similar ground plane.

- It should be noted that these antennas were designed to provide broadcast coverage from the exterior of an automobile, and therefore the radiation patterns from the test setups were not optimized for RSU operation, but did serve as a consistent means to compare broadcast characteristics across a broad range of intersections.

The Communication Test Kits (CTKs) from Task 4 were utilized to acquire the intersection testing data. The laptop computer, running the latest version of test software under Linux (V3.0.4), was mounted on a platform attached to the telescoping poles so that signal losses in the cables to the antennas would be minimized. The GPS antenna was placed nearby on the ground, typically in a position where interference from various objects (antenna ground plane, intersection features, test personnel, etc.) would be minimized. As such, there is often a minor offset of a few meters between the actual RSU broadcast location and the recorded GPS coordinates. Also visible in the following figures is a portable battery pack, which was used to power the GPS receiver unit.


**Figure 3. RSU at Detroit Area Test Location**
**Figure 4. RSU at Palo Alto Area Test Location**
**Figure 5. RSU at Detroit Area Test Location**
**Figure 6. RSU at Palo Alto Area Test Location**

Unless otherwise specified, Detroit area test parameters were set as follows for each data set reported:

- Broadcast frequency: 5.8GHz
- Broadcast power level: 100%
- Update rate: 10Hz
- Packet size: 500B
- Data rate: 6 Mbps

The San Francisco Bay area test parameters can be categorized into two parts: Testing with the Linux CTK software and testing with the Task 9 software. All of the Bay area tests were conducted with the Linux CTK software, with the exception of those that took place at the El Camino Real and 5th Avenue intersection, which utilized the VSCC Task 9 software. All testing with the Linux CTK had the following settings:

- Broadcast frequency: 5.8GHz
- Broadcast power level: 100%
- Update rate: 10 Hz
- Packet size: 500 bytes
- Data rate: 6 Mbps
- 10 feet height for the RSU antenna.

The testing with the Task 6D and Task 9 application had slightly different settings:

- Broadcast frequency: 5.89GHz
- Broadcast power levels: 100%, 50%, and 10%
- Data rate: 6 Mbps

In general, multiple test runs were completed for each directional approach to the intersection that was evaluated. After the test runs were completed, the test data was analyzed and evaluated. A cumulative summary for all directional approaches that we tested was then prepared, as well as individual summaries for each directional approach undertaken.

### *2.1.1 Baseline Evaluation and Test Equipment Verification*

Prior to performing tests at actual intersections, a variety of data was acquired at the Milford Proving Grounds. Previous experience had indicated that variability existed between some of the CTKs. This motivated the investigation of the communications performance of the CTKs, with both old and new antenna designs, and in the absence of traffic and obstructions. Figures 7 shows a sample of the data obtained while driving an out-and-back circuit on the long straight-away track.

The upper portion of Figure 7 serves to illustrate a new data visualization tool that is used to present test results.  Received packets are overlaid upon an aerial photo of the testing site, with each packet being color-coded to reflect the value of the Received Signal Strength Indicator (RSSI).  All of the RSSI plots in this report were generated using publicly available visualization software provided by Adam Schneider.

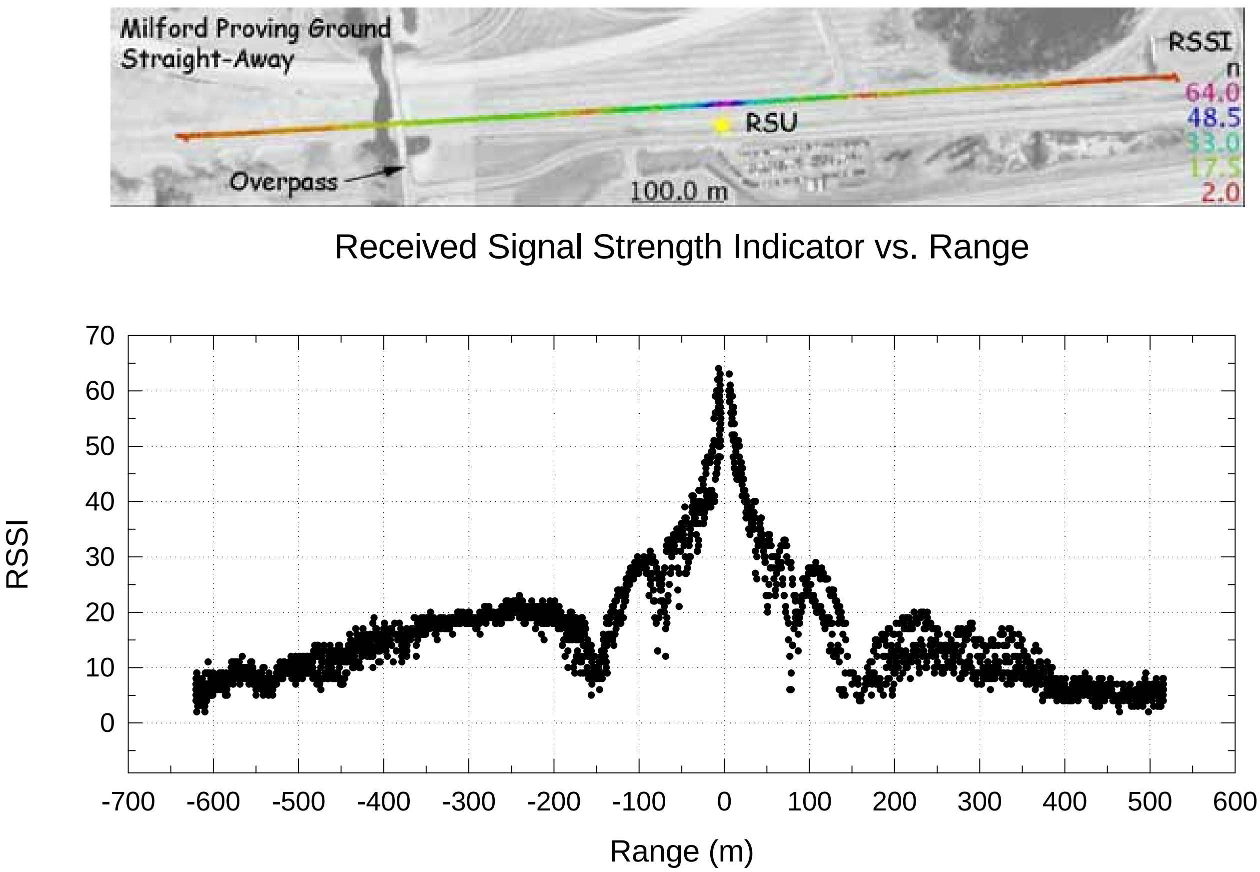



**Figure 7.  RSU Equipment Verification at Milford Proving Ground**

The lower portion of Figure 7 plots RSSI as a function of range from the improvised RSU, with data to the west arbitrarily plotted as negative range values and data to the east as positive range values.  It was observed that there were local minima in the RSSI at ranges corresponding to ~75m and ~150m, which reflected the geometry of the radio propagation for the setup, an anticipated phenomenon described in detail within the “Multipath Considerations” chapter of Appendix C.  Although the data to the west and east are not entirely symmetric, they are very nearly so, with the small differences likely due to the asymmetries built into the test stand and those due to the ground terrain, including the overpass to the west.

Based upon a variety of data sets similar to the one shown above, it was determined to be appropriate to use the new M/A-COM antennas for sending and receiving. Additionally, some variability between test kits was documented, and thus it was important, for the purposes of comparing results, to use the exact same equipment in all subsequent tests. As such, each component of the setup was carefully labeled and used for the entirety of the Detroit area testing.

After demonstrating adequate performance of the improvised test equipment, similar data was gathered at the intersections that were outlined in Section 1.2.1. The sections that follow describe the findings at each of these intersections.

### *2.1.2 Oakwood Boulevard & Michigan Avenue*

Five lanes extend out from this signalized intersection in each of four directions, and the intersection normally experiences heavy daytime traffic. For all of the data acquired, the RSU remained positioned on the southeast corner of the intersection, from which reasonable line of sight was provided in each direction of traffic (Figure 8).

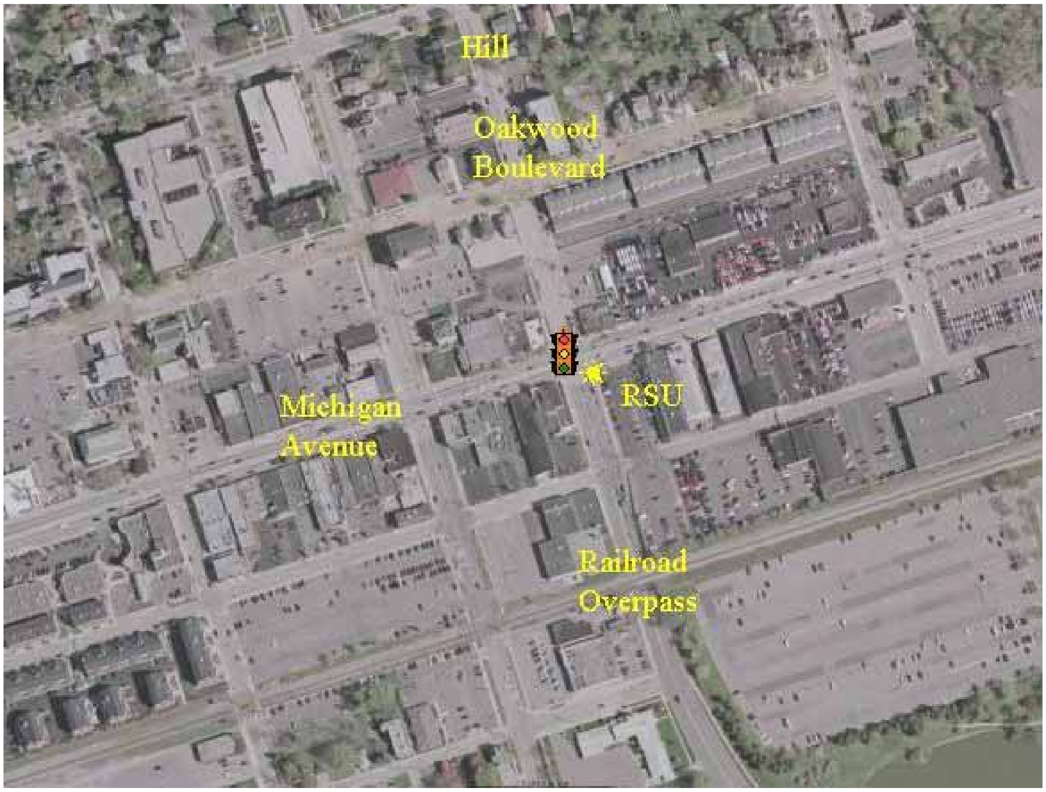



**Figure 8. Aerial View of the Oakwood/Michigan Intersection**

Oakwood Boulevard rises to the north and crests a small hill roughly a block and a half from the intersection. To the south, it descends, passing beneath a concrete buttressed railroad overpass and then bends out of sight around a corner. A mix of low buildings and parking lots characterizes this stretch of road, and there is relatively little vegetation of consequence. West of the intersection, Michigan Avenue also rises slightly for a block and a half, beyond which line of sight to the RSU is lost. Densely packed buildings and tree-lined sidewalks are present along this segment of road. To the east of the intersection, the road descends uniformly and there are fewer buildings and roadside obstructions.

The test vehicle received data from the RSU while driving along each direction of travel at the intersection. Figure 9 shows the same overhead view of the intersection, but the received packets from the test runs are overlaid upon the aerial photo, with each packet color-coded to correspond with the value of the Received Signal Strength Indicator (RSSI). The RSSI values are listed in the lower left portion of the figure, and as expected, the highest values are found where the test vehicle travels in closest proximity to the RSU.


**Figure 9. Aerial View Overlaid with Color-Coded RSSI Values**

Proceeding northbound on Oakwood Boulevard in medium density traffic, only 3 packets were dropped at distances to the RSU less than 100m. While reception on the northbound side was entirely consistent with the apparent line of sight to the hillcrest, considerable reception was obtained on the southbound side well beyond line of sight, despite the drop in elevation to pass under the railroad tracks and the subsequent bend present in the road. Clearly, there were reflected signals present due to the physical structures involved. Note that although the GPS signal was lost under the railroad overpass, radio data was still being acquired. Reversing the direction and driving southbound produced similar results, with only 4 packets lost within ~100m of the intersection (Figure 10).


**Figure 10. Views from the Oakwood/Michigan Intersection**

Heading eastbound on Michigan Avenue in very dense traffic, 3 packets were lost within ~100m of the intersection. While waiting at a red light at the intersection one block west of the RSU, a mere 8 packets were dropped, despite the tightly packed arrangement of vehicles. The westbound direction had a slightly extended range (relative to the eastbound heading), presumably due to the better geometric line of sight to the vehicle. In this case, 2 packets were dropped within ~100m of the intersection. Figure 11 shows the CTK diagrams of the packet reception versus distance. The results demonstrate that packets can be received near this intersection under heavy traffic conditions and with an RSU situated in a less-than-optimal position.

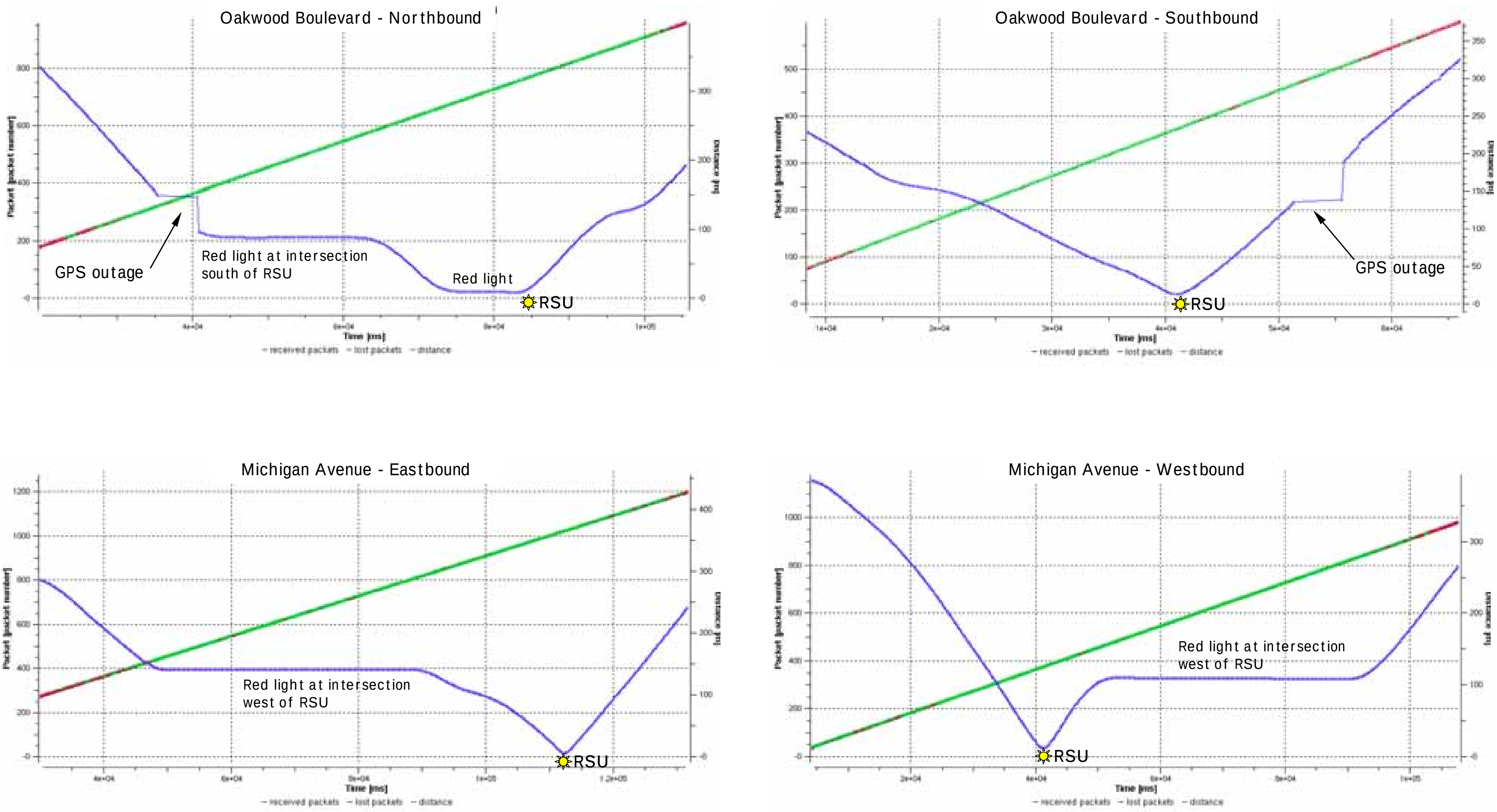



**Figure 11. CTK Plots of the Oakwood/Michigan Intersection**

### 2.1.3 Crooks Road & Big Beaver Road

This intersection has three lanes of traffic in the east and westbound directions, and these lanes are continually full of moving traffic during the daytime hours. The north and southbound directions on Crooks Road also have several lanes of traffic, but are not separated by the medial strip (with small trees and bushes) that is found on Big Beaver Road.

Foliage on the medial strip occasionally blocked the line of sight for the RSU, as shown by dropped packets indicated by callouts (1) in Figure 12. One method to help address this issue might be to package the RSU in the traffic light or at a similar height.

Buildings encircle the intersection - some, although not all, are quite tall - but are far removed from the intersection by large parking lots. The RSU was placed on the medial strip on the eastern side of the intersection, and was moved from north to south as necessary to provide best line of sight for each individual data set.

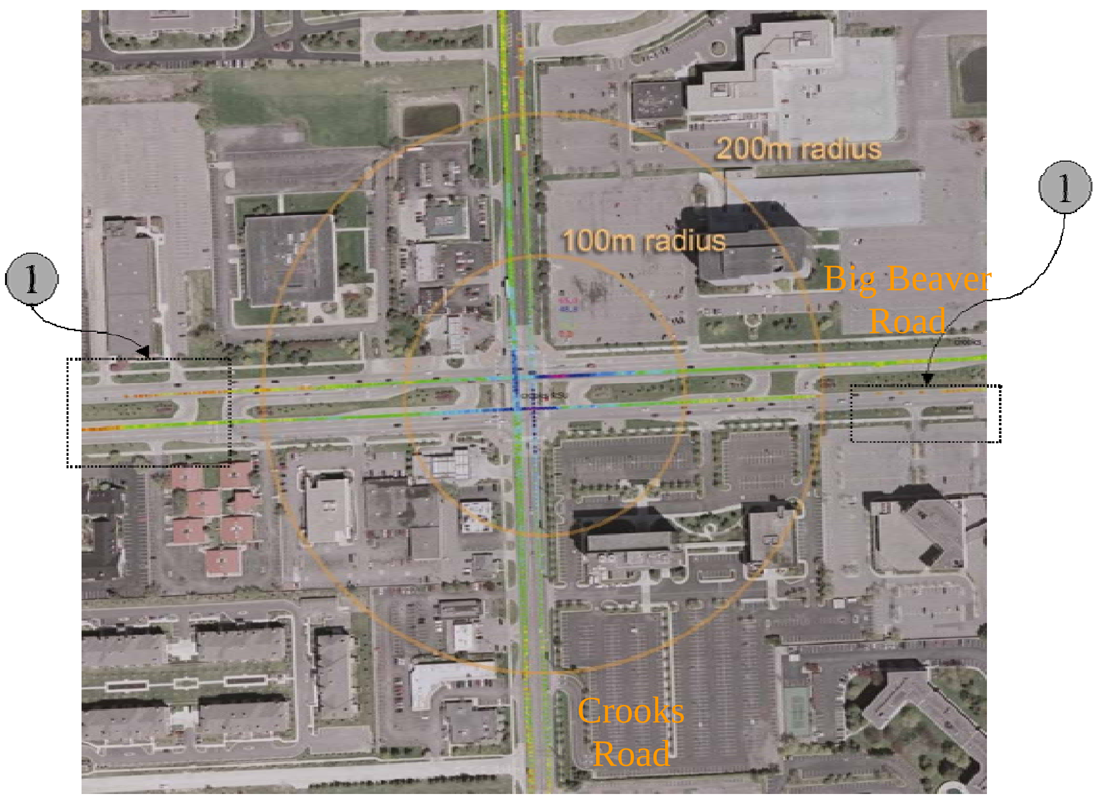



**Figure 12. RSSI Plot of the Crooks/Big Beaver Intersection**

Traveling northbound on Crooks Road, the test vehicle was stopped at a traffic light 200m beyond the intersection of interest and, meanwhile, traffic behind the receiver was interfering with the signal. This would not be a concern for an intersection-based application since the vehicle had already proceeded through the intersection.

In the other directions of travel (Figure 13), line-of-sight interference caused a low RSSI at a significant distance from the intersection. Yet most of the packets were still received, as shown by callouts in Figure 14. The packets dropped in (2) would not be a concern since the vehicle had already proceeded through the intersection.

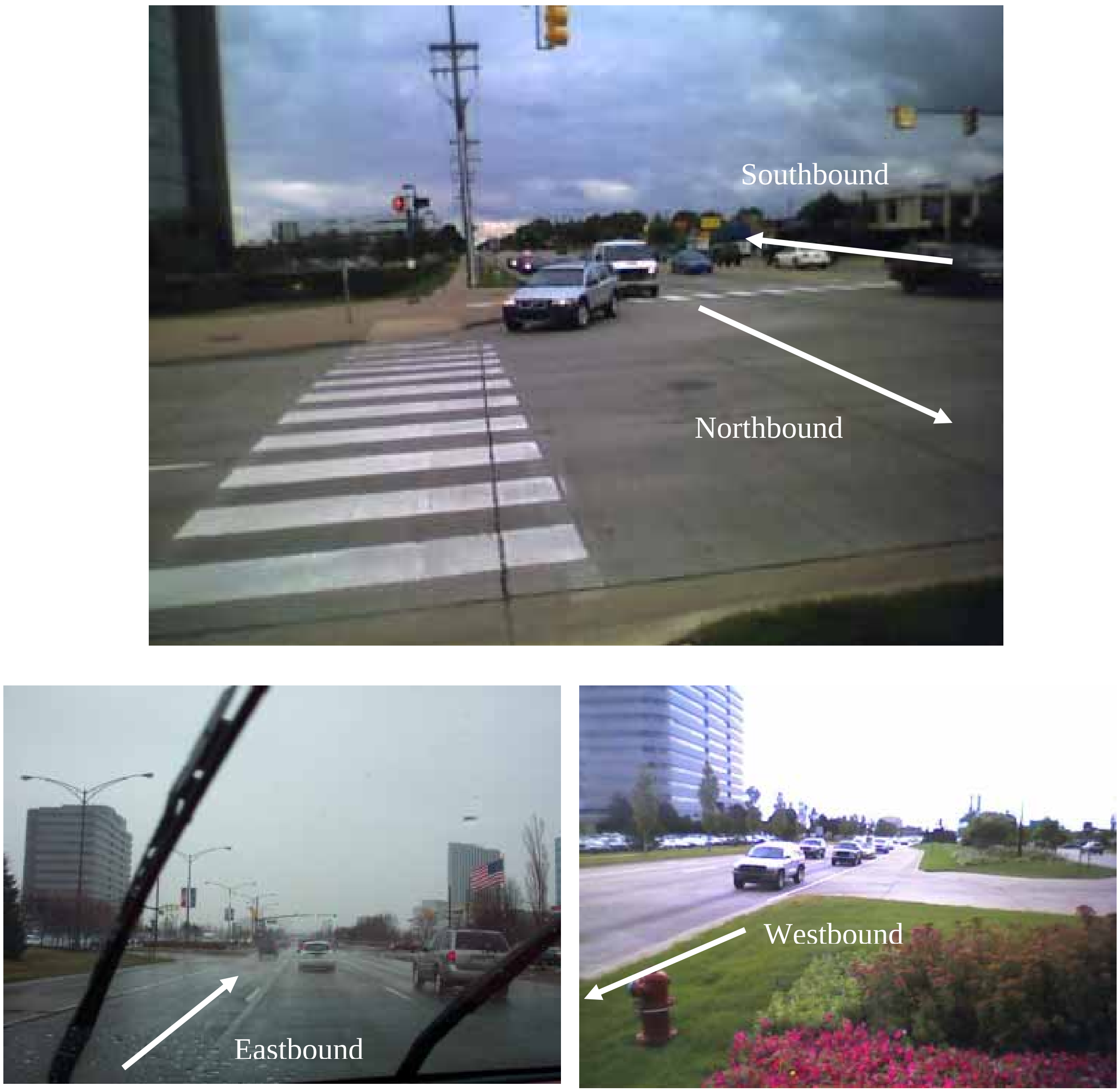



**Figure 13. Views of the Crooks/Big Beaver Intersection**

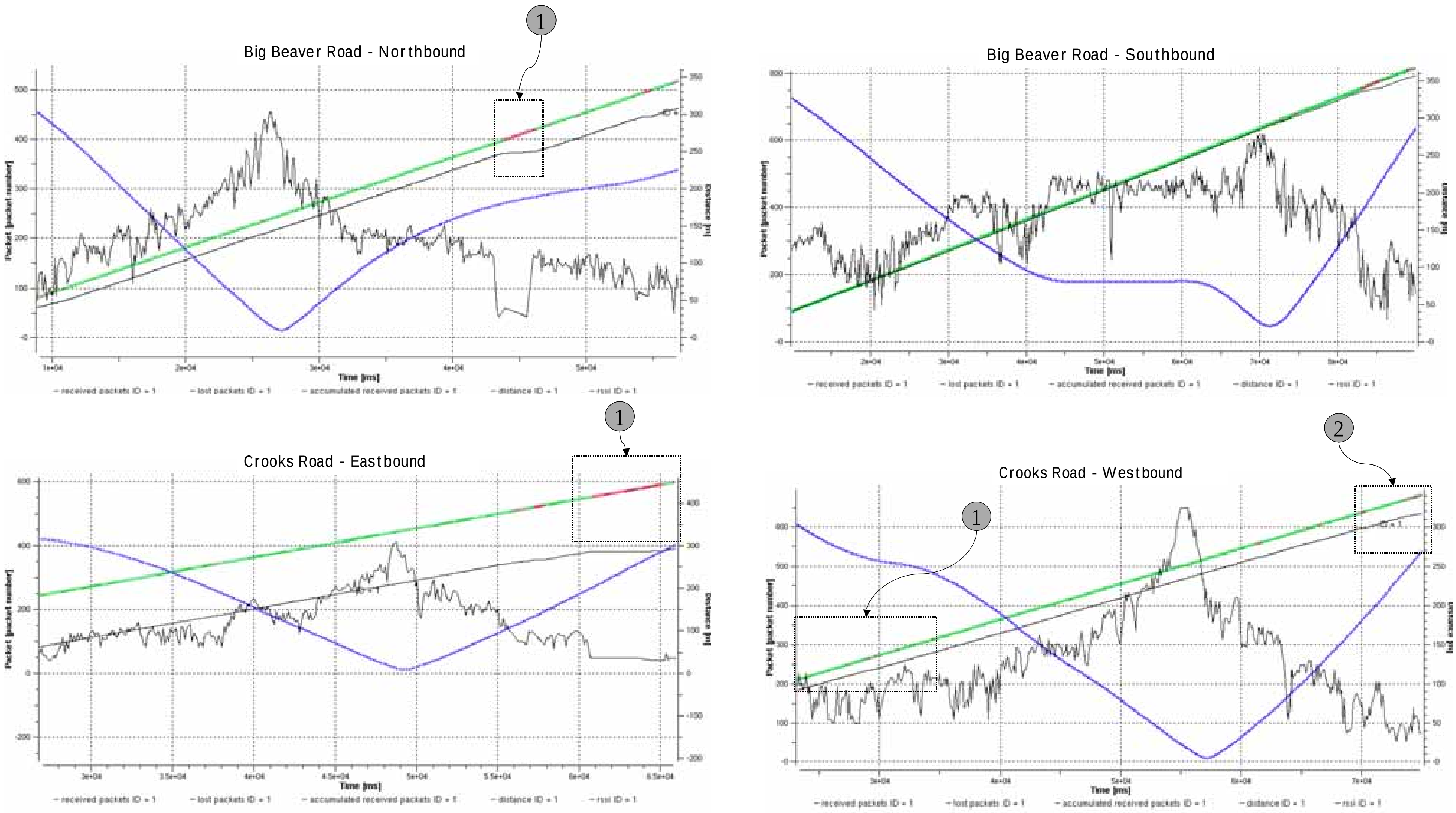



**Figure 14. CTK Plots of the Crooks/Big Beaver Intersection**

### *2.1.4 Santa Clara Street & Market Street*

The intersection of Santa Clara and Market in San Jose had heavy traffic during the time of the testing (Figure 15). Both Santa Clara and Market Streets have double lanes in both directions. There are trees and closely packed high rises along both sides of Market. There is a traffic light at the intersection and both roads have a center lane for left-turns at the intersection. The RSU was placed on the northeastern side of the intersection to provide line-of-sight to north and southbound traffic on Market Street.

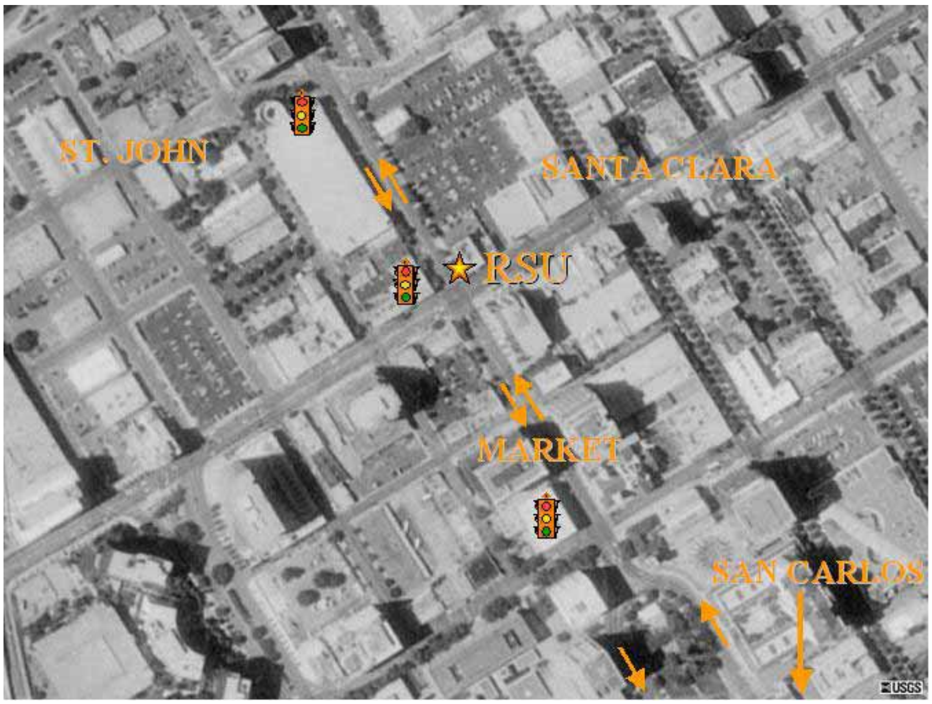



**Figure 15. Aerial View of Santa Clara/Market Intersection**

The intersection of Santa Clara and Market has closely packed high rises all around. The test car started off near the RSU (intersection) and traveled north onto Market (Figures 16 and 17). It turned back at St. John and passed the RSU. Then it turned back again at San Carlos and returned to the RSU.

Packets were dropped frequently along the test route due to heavy traffic and no line-of-sight between the RSU and the OBU. One possible method to improve the packet reception at this type of intersection would be to position the RSU at a higher height to improve the line-of-sight between the sending and receiving antennas.


**Figure 16. RSSI Plot and Views of Market/Santa Clara Intersection**

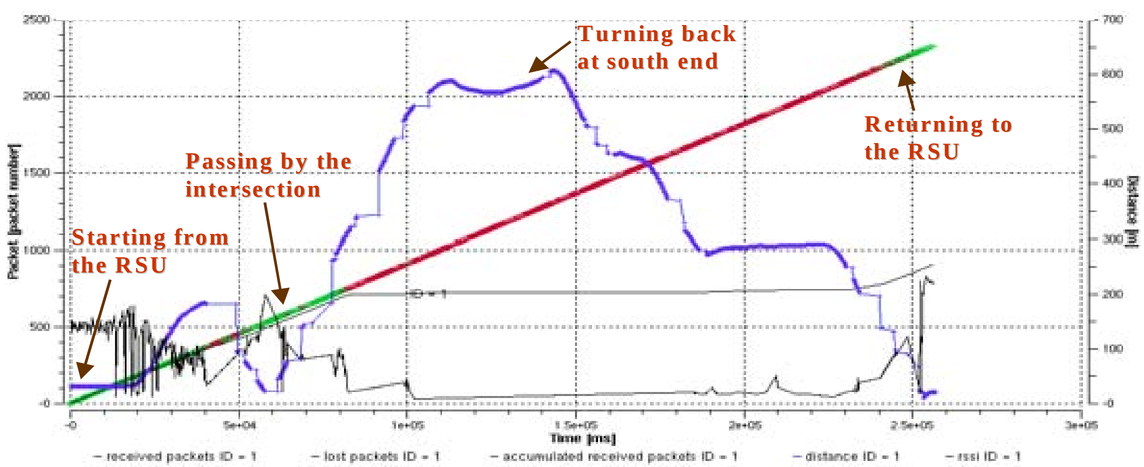



**Figure 17. CTK Plot of the Market Street Test Route**

### 2.1.5 *Hillview Avenue & Hanover Street*

The intersection of Hillview and Hanover in Palo Alto has light traffic during the daytime. Both Hillview and Hanover have a single lane in both directions. The north end of Hanover is slightly uphill and the south end has a 90º bend to the west. There are many trees and office buildings along both sides of Hanover. There is a traffic light at the intersection and both roads have a center lane for left-turns at the intersection. The RSU was placed on the western side of the tee-junction to provide line-of-sight to the north and southbound traffic on Hanover (Figure 18).

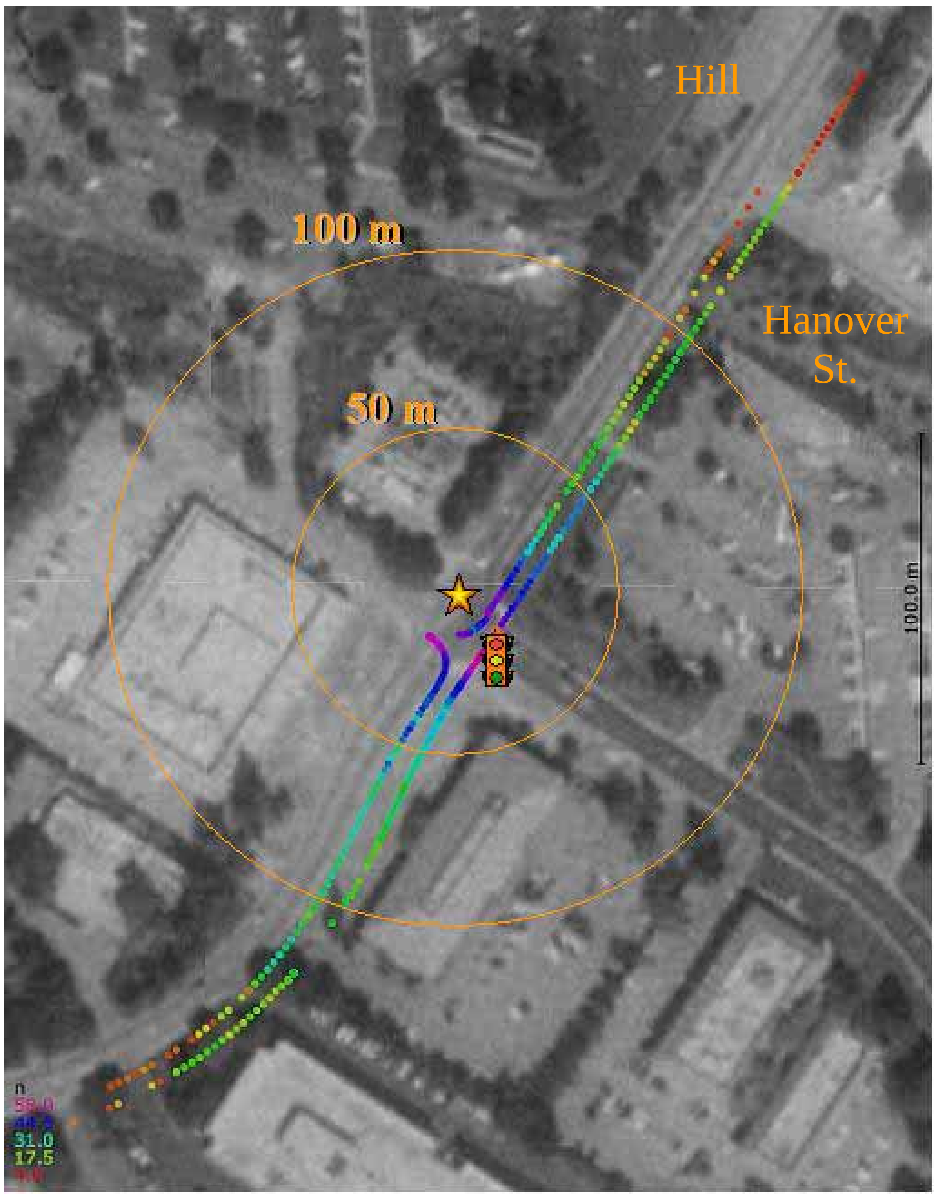



**Figure 18. RSSI Plot for the Hanover Test Route**

The test car started off from the RSU onto southbound Hanover (Figures 19 and 20). It turned back after the curve, then passed through the intersection. It continued and went slightly uphill on northbound Hanover. It finally turned back ~300m away from the intersection and returned to the RSU. Occasionally the hill or objects and terrain along the edge of the curving Hanover Road obscured the line-of-sight.


**Figure 19. Views of the Hillview/Hanover Intersection**

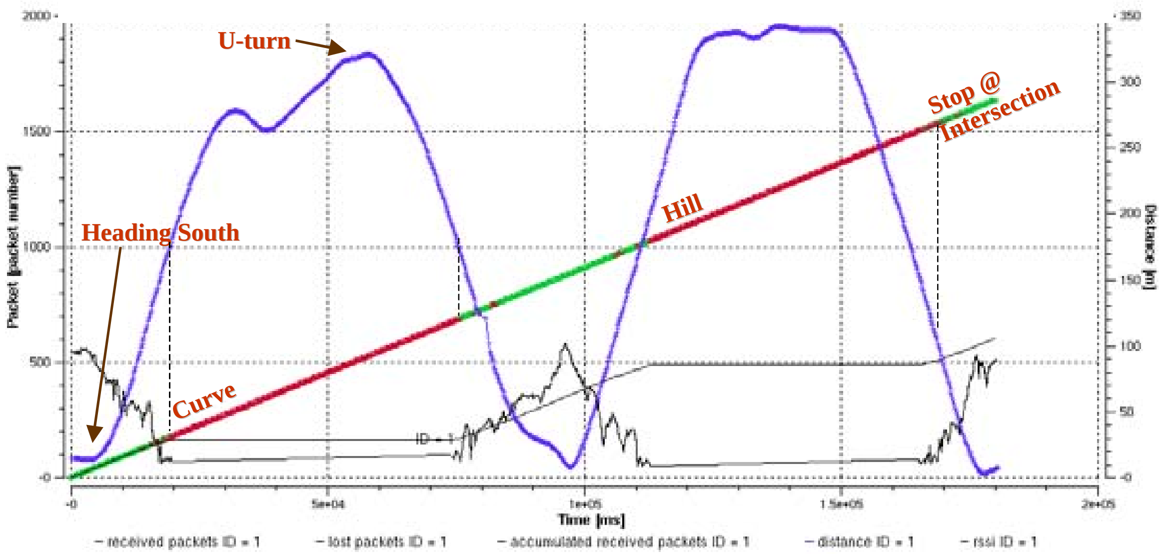



**Figure 20. CTK Plot for the Hanover Test Route**

### *2.1.6 Woodward Avenue & I-696 Service Drive*

This intersection has four lanes in the southbound direction and five lanes in the westbound direction, and both directions include a left turn lane (Figure 21). There is medium to heavy traffic during the day. The traffic from southbound Woodward Avenue branches off, passing under a large overhanging parking garage before reaching the traffic signal on the I-696 service drive where the RSU is located. In addition to the parking structure, there are numerous other features that might impact communications, including a water tower, below-surface-level freeways along both test roads, and a number of concrete overpasses.

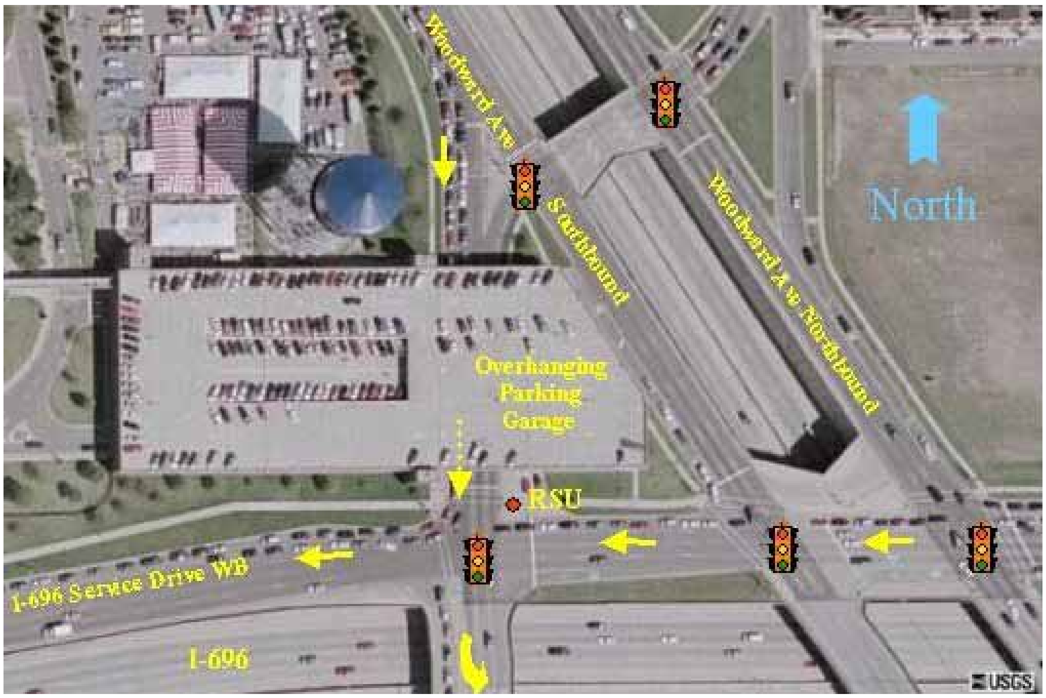



**Figure 21. Woodward/I-696 Service Drive Intersection**

Although there appeared to be a significant amount of obstructions at this intersection, reception results were much better than anticipated, as shown in Figure 22. Note that reception of the GPS signal was blocked while the vehicle was under the parking garage in test run #2, and the packets that were received during this portion of the test were plotted at the point where the GPS signal was reestablished. This run was concluded when the vehicle turned left onto the eastbound I-696 service drive.

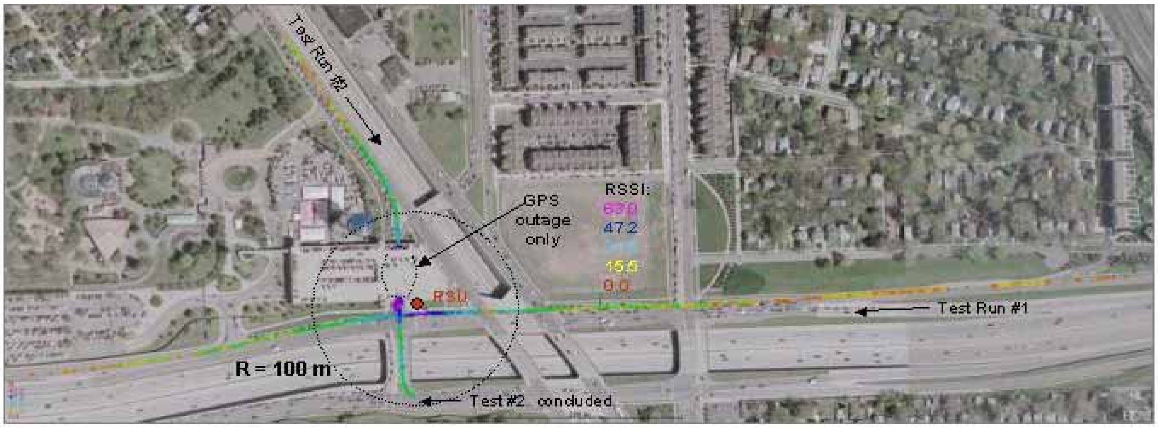



**Figure 22. RSSI Plot of the Woodward/I-696 Service Drive Intersection**

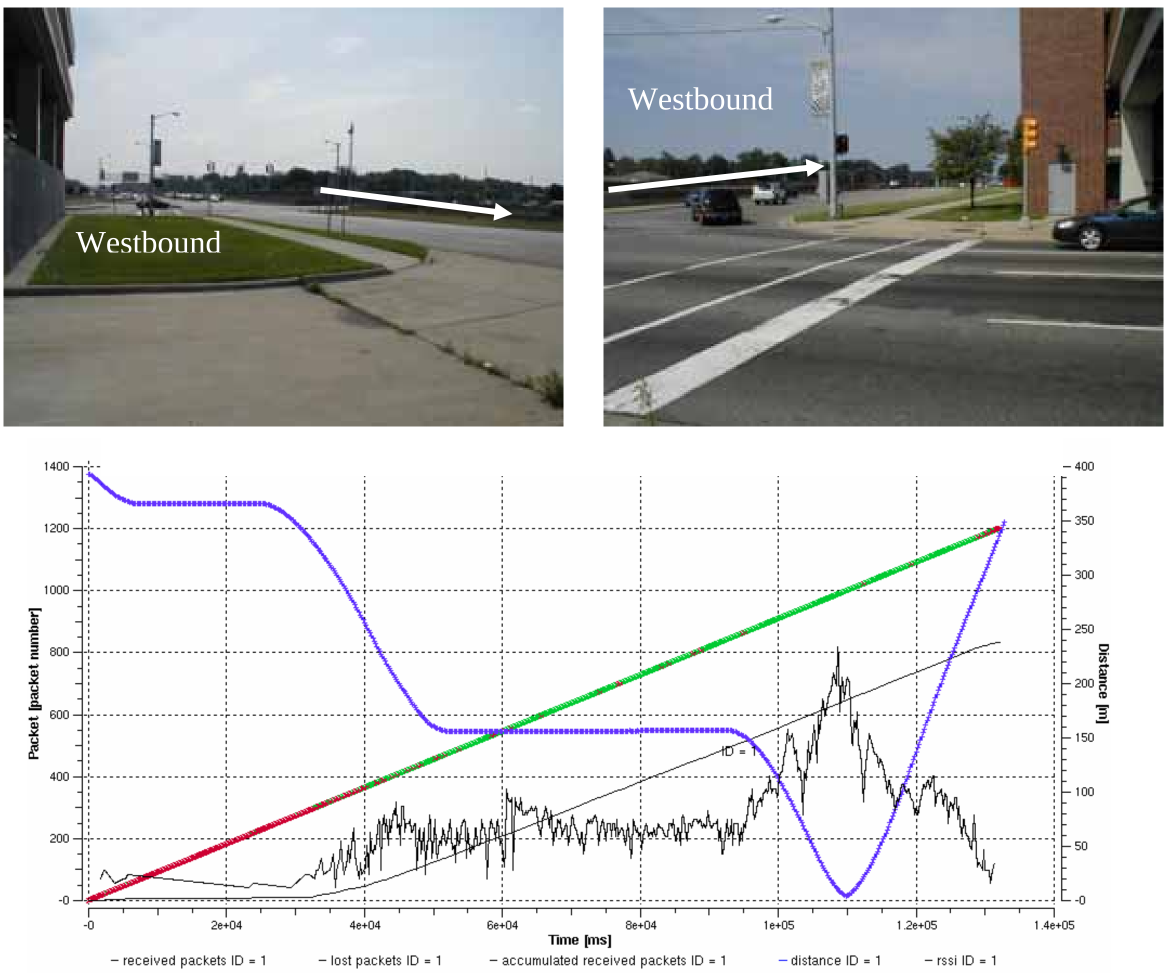



**Figure 23. Views and CTK Plot of the I-696 Service Drive Test Route**

For westbound I-696 Service Drive (Figures 22 and 23), packets were initially blocked by heavy traffic at a significant distance from the RSU. The cumulative packet reception rate as the vehicle approached the intersection from 250m was 85 percent, and the rate from 100m was 100 percent.

For southbound Woodward Avenue and its exit road to the I-696 service drives (Figures 22 and 24), packets were initially lost due to blockage of terrain and foliage alongside the curving roadway. Surprisingly, packet reception began at a distance of approximately 300m while line-of-side was still blocked. As the vehicle passed beneath the parking structure, the GPS signal was lost but packets continued to be received. GPS reception resumed when the vehicle moved beyond the parking structure. The test was concluded when the vehicle turned around the corner and onto the eastbound I-696 service drive. The cumulative packet reception rate as the vehicle approached the intersection from 250m was 89 percent, and the rate from 100m was 99 percent.


**Figure 24. View and CTK Plot for the Woodward Test Run**

## *2.1.7 El Camino Real & 5th Avenue*

The intersection of El Camino and 5th in Atherton had medium traffic during the time of the testing. El Camino has three lanes in each direction and two additional lanes for left-turning onto 5th. 5th has two lanes in each direction and one left turn lane for southbound El Camino. A moderate amount of trees and buildings are along both sides of El Camino and the south-end is slightly curved. There is a traffic light at the intersection. The RSU was placed on the northeastern corner of the tee-junction to provide line-of-sight to north and southbound traffic on El Camino, as well as traffic on 5th. The testing was done at three power levels: 100 percent, 50 percent, and 10 percent.

The test car traveled westbound on 5th, right-turned onto El Camino and headed north. It turned back at approximately 400m away from the RSU. It went past 5th and continued along southbound El Camino. Then it turned back again at about 400m away and returned to the intersection. It right-turned onto 5th and turned back at about 200m away. In the 100 percent power test, the reception is shown in Figure 25. There were occasional dropped GPS signals and packets due to trees and no line-of-sight.

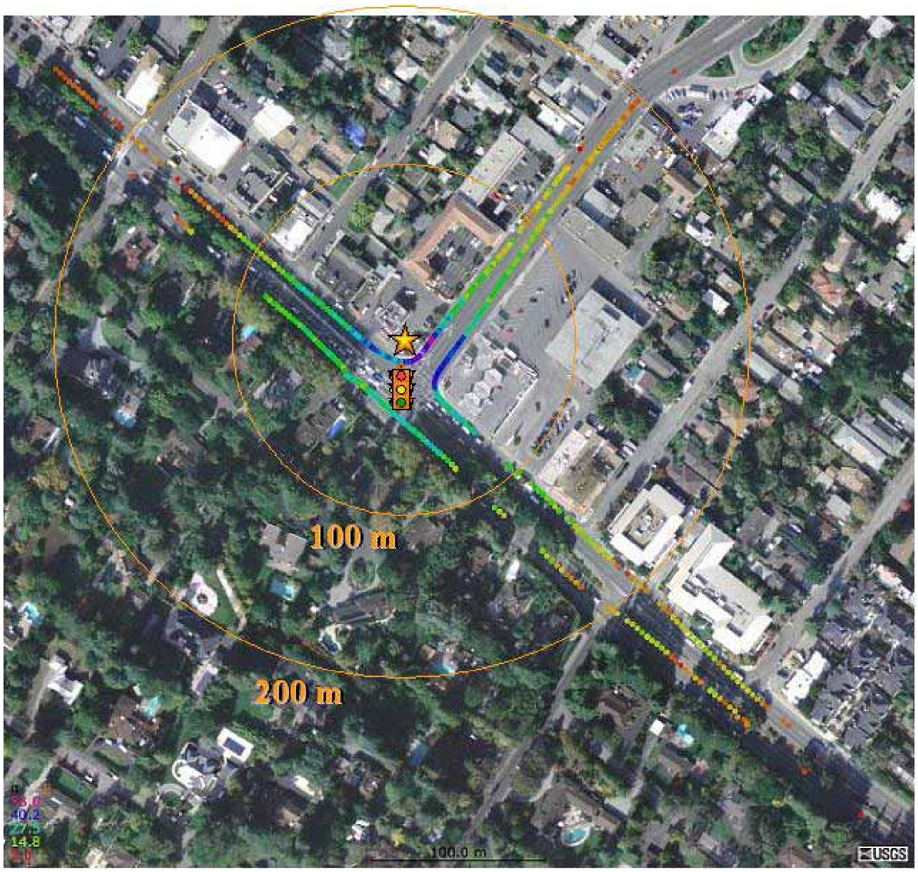



**Figure 25. RSSI Plot for El Camino Real/5th at 100% Power (20 dBm)**

In the 50 percent power test (Figure 26), there were less packets received and they had slightly lower RSSI values, compared with the results at 100 percent power. The receiver could not detect as many packets as it could in the case of 100 percent power. In the 10 percent power test (Figure 27), there were even less packets received and they had even lower RSSI values, compared with results at 50 percent power. The receiver could not detect as many packets as it could in the case of 50 percent power.

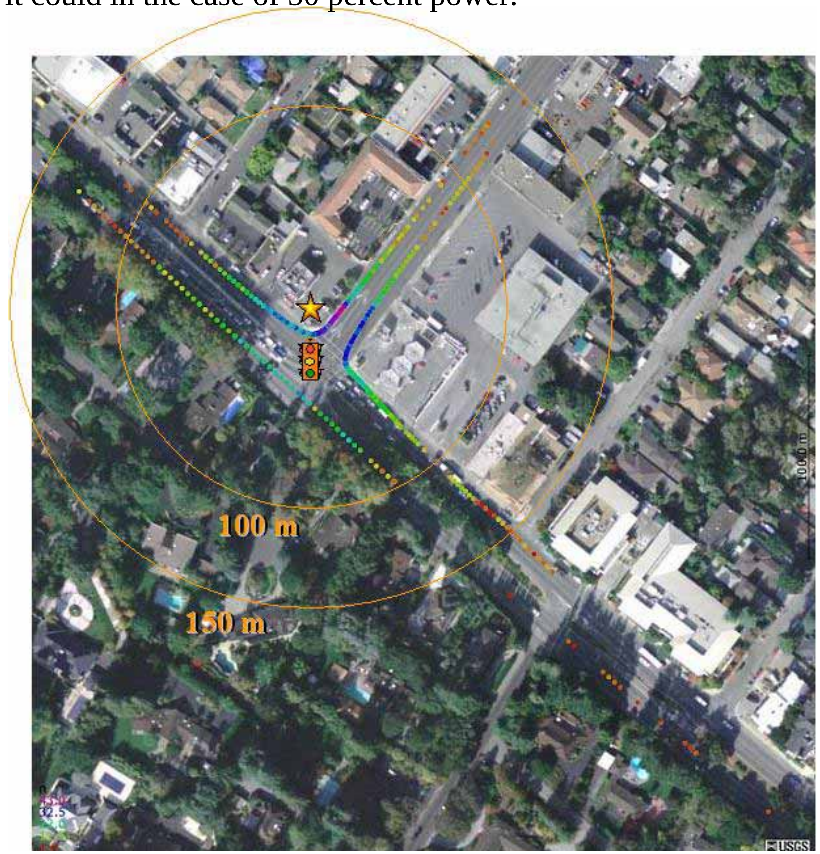




**Figure 26. RSSI Plot for El Camino/5th at 50% Power (17 dBm)**
**Figure 27. RSSI for El Camino/5th at 10% Power (10 dBm)**

### 2.1.8 *Woodside Road & Churchill Avenue*

The intersection of Woodside and Churchill in Redwood City has medium traffic during daytime. Woodside has two lanes for both directions and Churchill has one for both directions. Both directions on Woodside away from the intersection have up-hills and the south end is slightly curved to the west. There are many trees along both sides of Woodside. Woodside has a left turn lane with a traffic light at the Churchill intersection. The RSU was placed on the northeastern corner to provide line-of-sight to north and southbound traffic on Woodside (Figure 28).

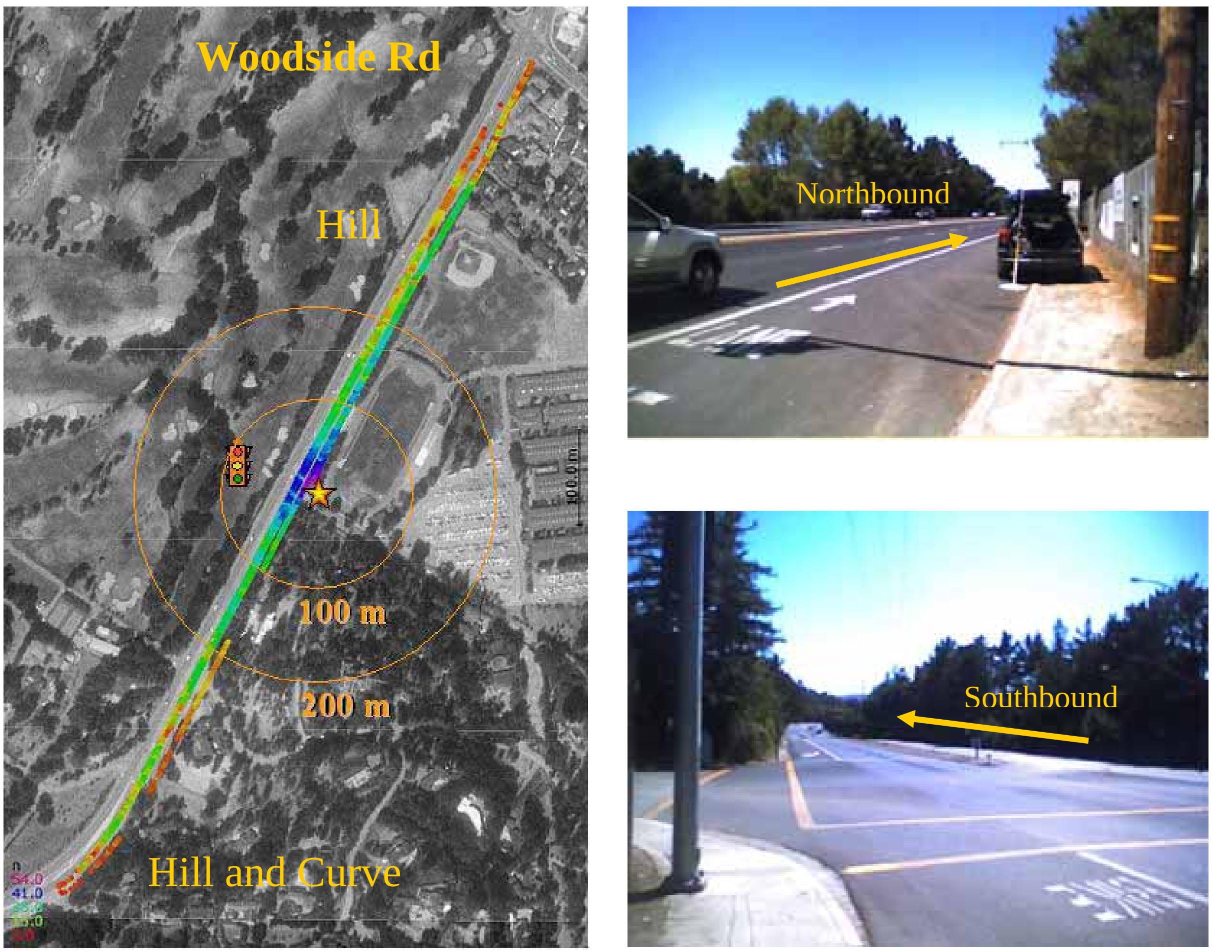



**Figure 28. RSSI Plot and Views of the Woodside Test Run**

The test car received signals except at locations where the line-of-sight was obscured by hills or road curvature (Figures 28 and 29). Reception faded at both ends of the test route (~500m away).

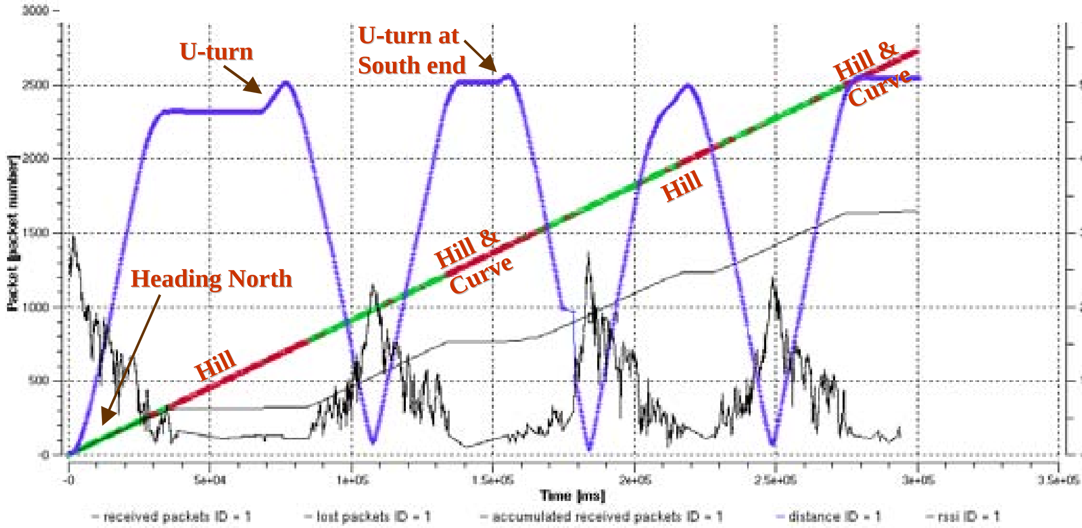



**Figure 29. CTK Plot for the Hillside Test Run**

## 2.1.9 *Country Club Drive & 12 Mile Road*

Eastbound 12 Mile has 2 lanes and a right turn lane. Westbound 12 Mile has 2 lanes and a left turn lane, and this intersection experiences light to heavy traffic conditions depending on the time of day. Vehicles traveling East on 12 mile have an obstructed line of sight to the RSU due to trees located on the median strip due to trees. Country Club Drive has 2 lanes in each direction separated by a median strip. This road also has an obstructed line of sight to the RSU due to several trees.

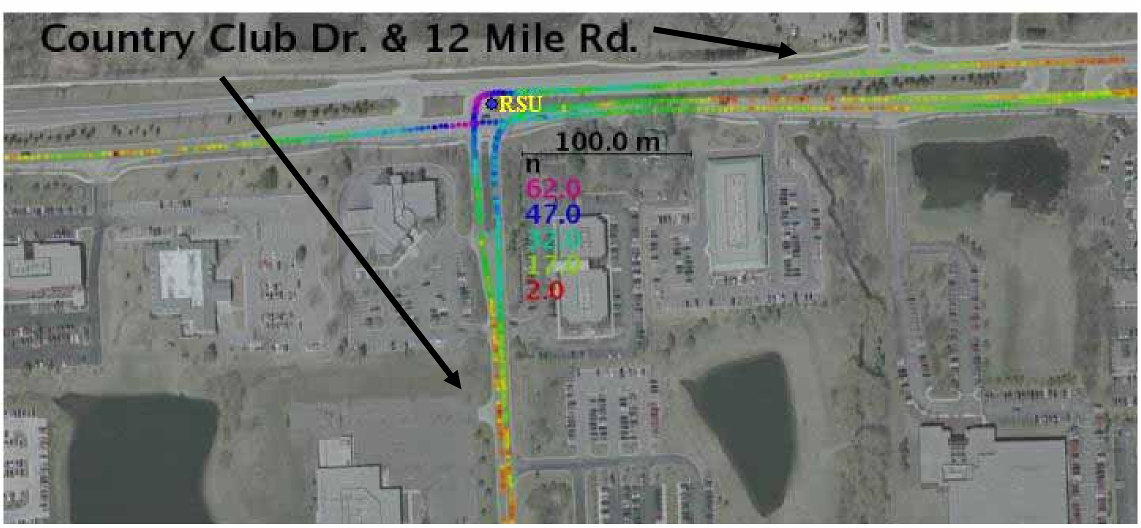



**Figure 30. RSSI Plot for the Country Club/12 Mile Intersection**

The test vehicle first traveled eastbound on 12 Mile Road straight past the RSU (Figure 30). A few packets were lost at around 200 m on either side of the RSU, possibly due to blockages from trees.



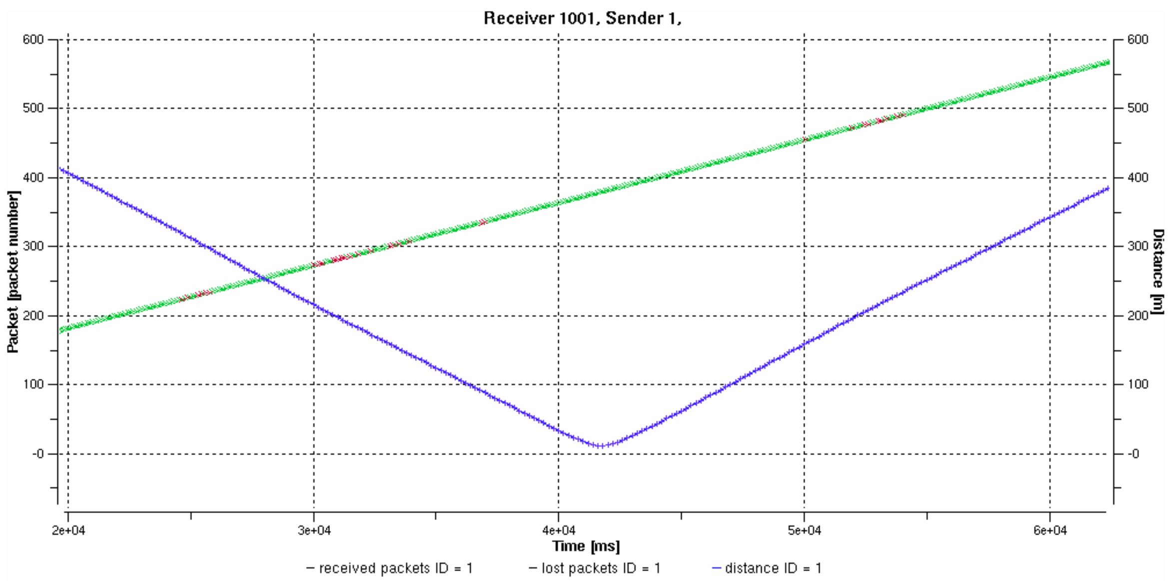
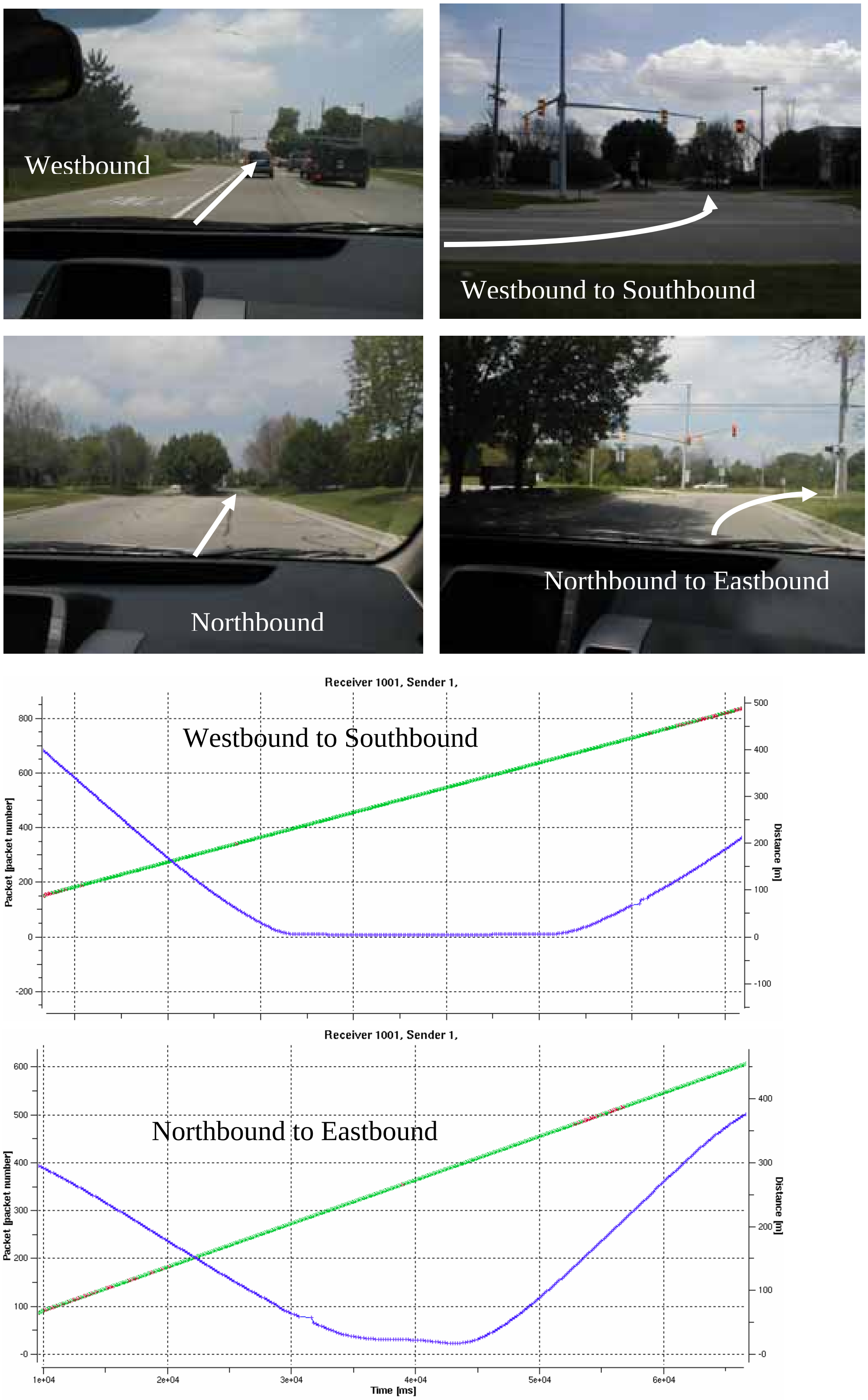



**Figure 31. Views and CTK Plot for Eastbound 12 Mile Test Run**

Next, the test vehicle U-turned and headed westbound on 12 Mile Road back toward the RSU (Figure 31). The vehicle turned southbound onto Country Club Drive and passed the RSU. Packets were lost going southbound while moving away from RSU due to blockages from trees. The test vehicle then turned around and headed northbound on Country Club Drive, turning right at the intersection past the RSU onto eastbound 12 Mile Road. A few packets are lost going both north and east due to blockages from trees (Figure 32).




East Test Routes

## *2.1.10 Auburn Road & Squirrel Road*

This intersection had light traffic during the time of testing. Auburn Road has two lanes in each direction, while Squirrel Road has one lane in each direction and a center left turn lane. Squirrel Road curves suddenly just north of the intersection, and line-of-sight to the RSU is blocked by terrain along the curving roadway. Even though line-of-sight was obstructed from the RSU, the vehicle traveling northbound on Squirrel Road communicated with the RSU for distances far beyond the line of sight (Figure 33).

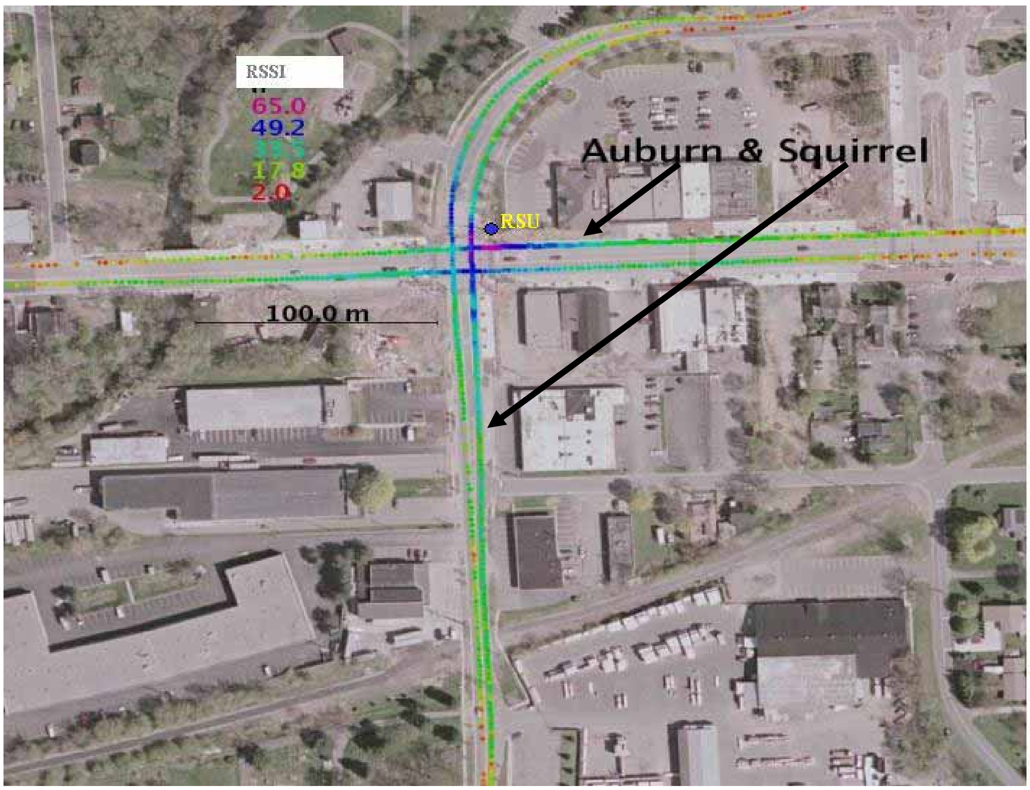



**Figure 33. RSSI Plot for Auburn/Squirrel Test Runs**

Traveling northbound on Squirrel Road, 100 percent of packets were received starting at about 275 m since there is clear LOS in this direction on Squirrel Road (Figure 34). Packets were eventually lost due to blockage of terrain alongside the curving roadway on the south side of Squirrel Road. Packet reception ended at a distance of approximately 130m with line-of-sight blocked.



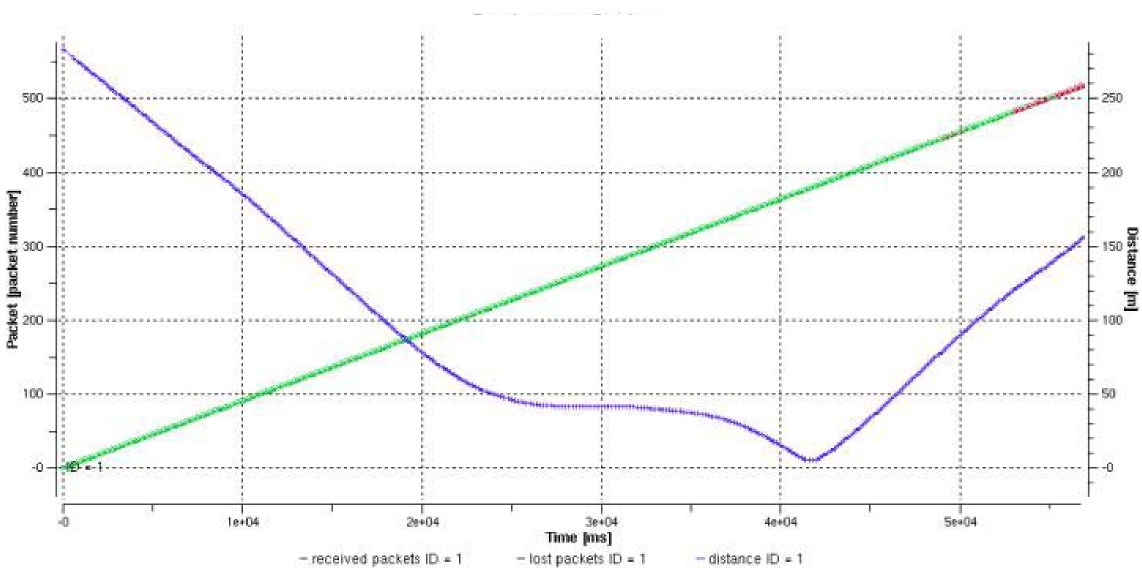



**Figure 34. Views and CTK Plot for the Southbound Squirrel Test Run**

Traveling southbound, packets were initially lost due to blockage of terrain alongside the curving roadway on the south side of Squirrel Road (Figure 35). Packet reception began at a distance of approximately 175m while line-of-sight was still blocked. As the vehicle passed the intersection, a large truck blocked the LOS between the RSU and OBU, causing some intermittent communication loss. The test was concluded when the communications between the RSU and OBU was lost at distance of 300 m.


**Figure 35. Views and CTK Plot for the Southbound Squirrel Test Run**

Eastbound on Auburn Road, the test vehicle initially received 100 percent of the packets at about 200 m since there is clear LOS going in this direction (Figure 36). Trees and parked vehicles obstruct the line of sight and communication beyond 200m.

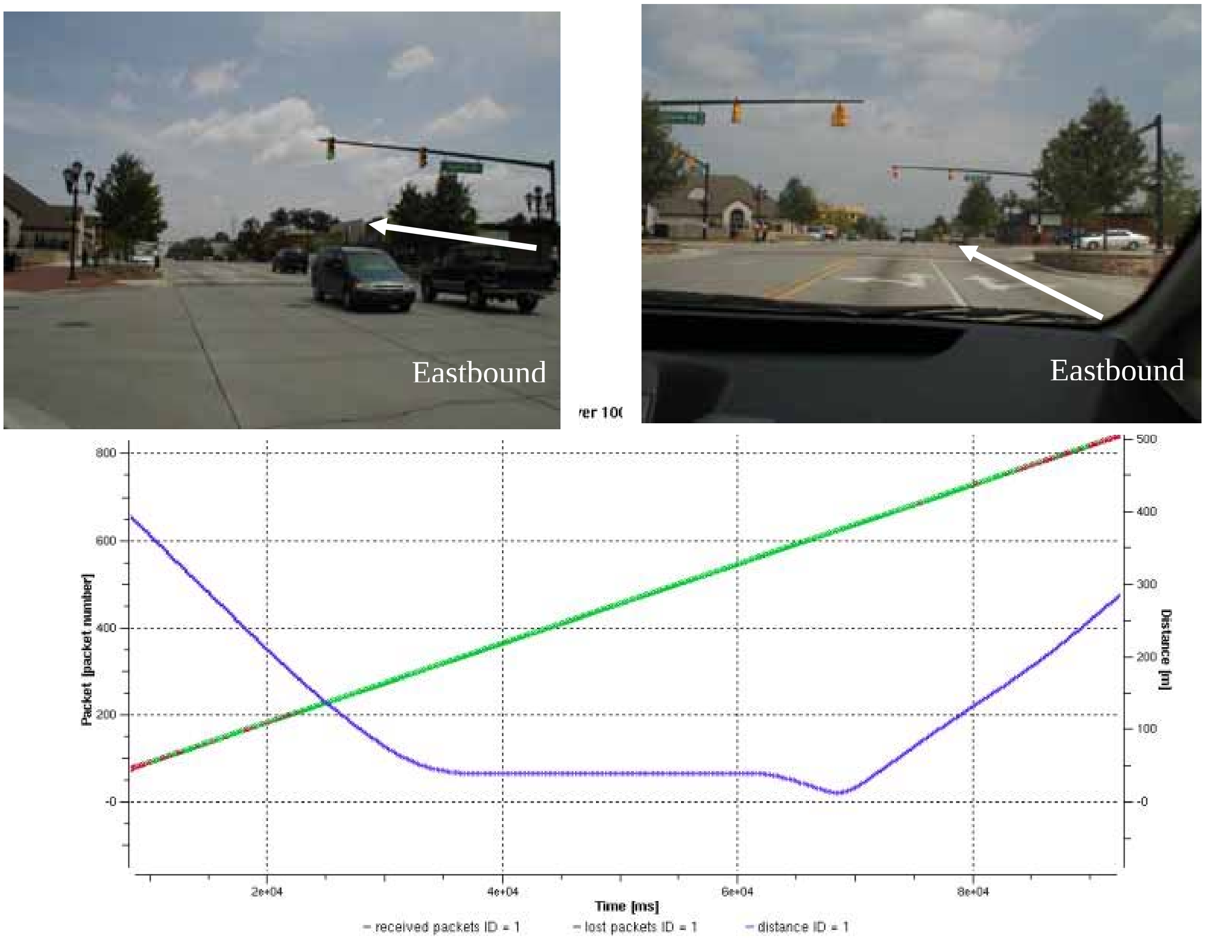



**Figure 36. Views and CTK Plot for the Eastbound Auburn Test Run**

Traveling westbound on Auburn Road, packets were received well up to about 200 m on either side of the RSU going in this direction. Packets were lost for a short duration due to LOS blockage by a large white truck (Figure 37).

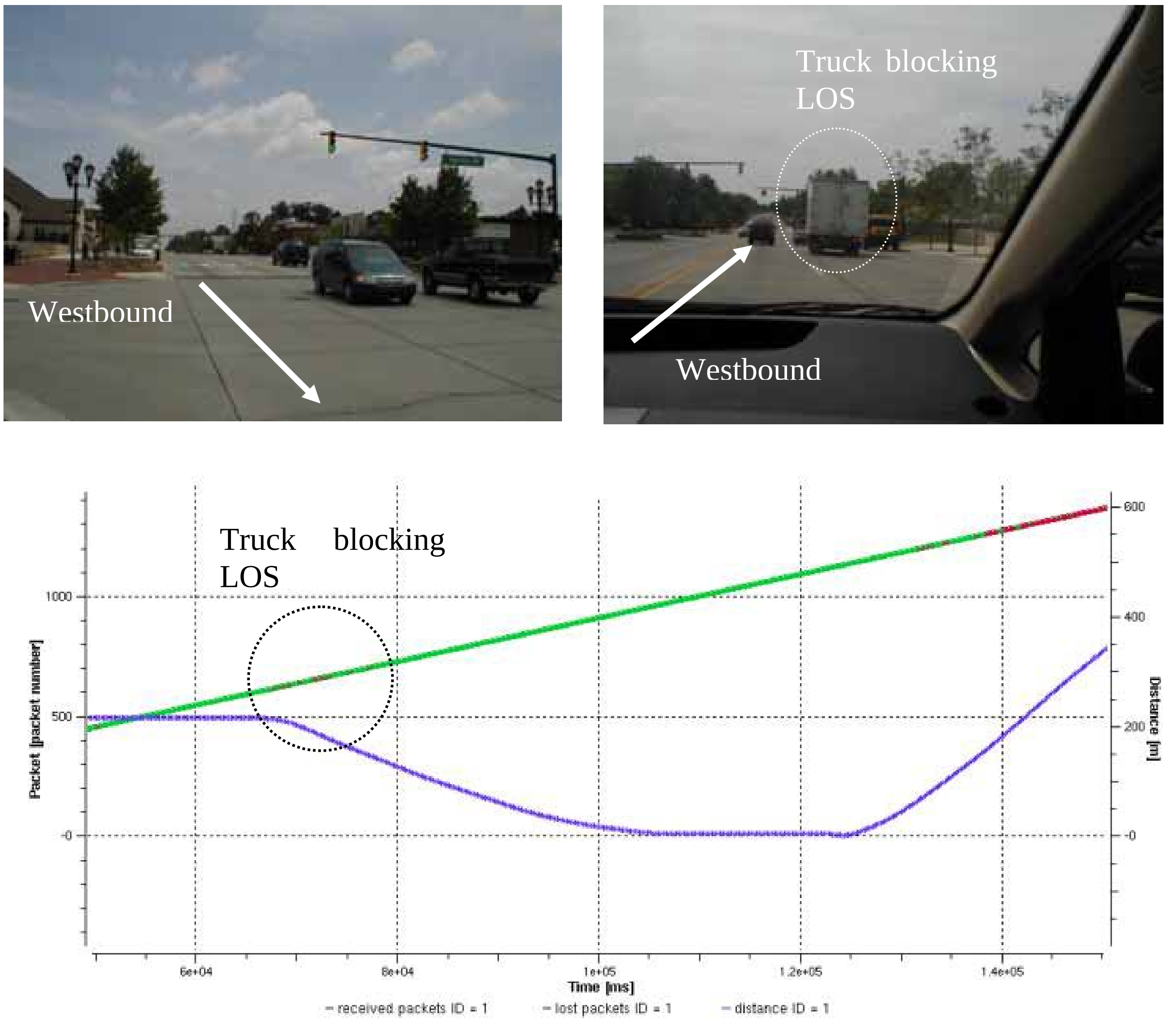



**Figure 37. Views and CTK Plot for the Westbound Squirrel Test Run**

### *2.1.11 Sand Hill Road & Whiskey Hill Road*

This portion of Sand Hill runs relatively north-south, and Whiskey Hill intersects Sand Hill at an angle, coming from the north-east. The intersection of Whiskey Hill and Sand Hill does not have a traffic signal. There is a triangle-shaped median in the middle of the intersection, separating Sand Hill from two branches of traffic that run southbound on Whiskey Hill. Traffic on Whiskey Hill that will continue south yields to and merges with southbound traffic on Sand Hill. Traffic on Whiskey Hill that will turn north onto Sand Hill has a stop sign. The intersection is a relative low-point - there are up-hills in both directions on Sand Hill going away from the intersection. Whiskey Hill also rises from the level of the intersection. There are few buildings nearby, though there are a number of tall trees and shrubs (Figure 38).

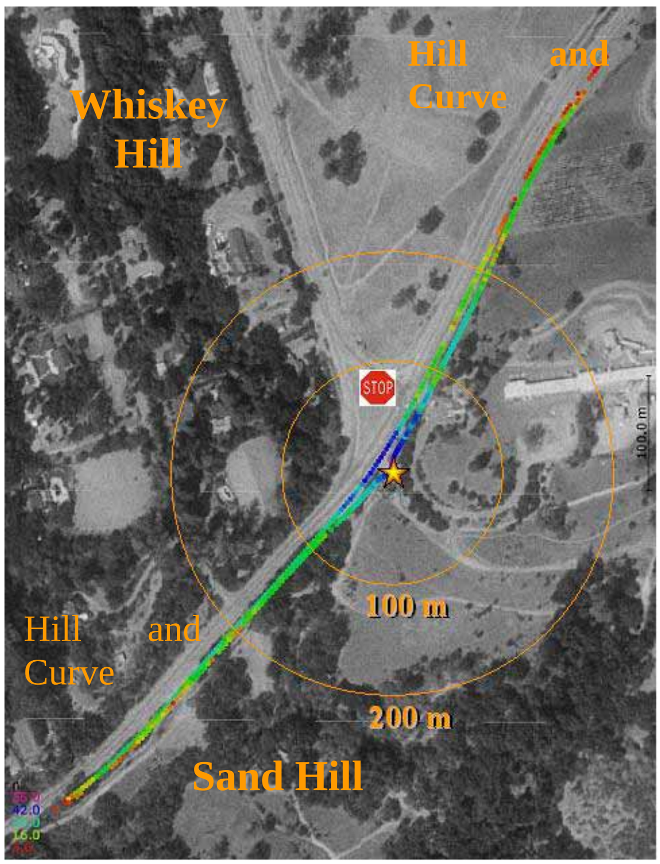



**Figure 38. RSSI Plot for Sand Hill Test Route**

The test car started from the RSU (intersection) and traveled northbound on Sand Hill.  It turned back and passed thru the RSU.  Then it turned back again and returned to the RSU.  Occasional packets were dropped due to the long distance or no line-of-sight from RSU to OBU (Figure 39).

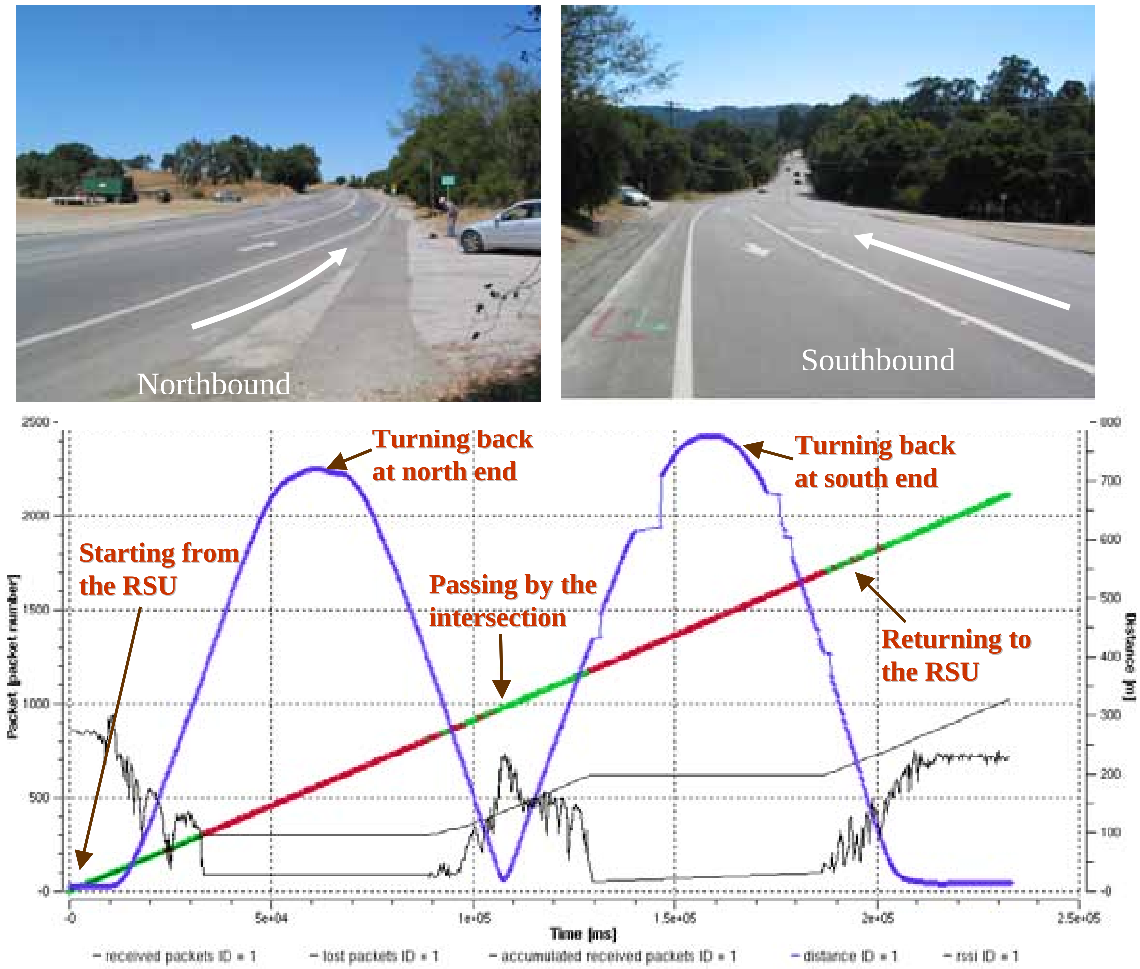



**Figure 39.  RSSI Plot for Sand Hill Test Route**

### *2.1.12 Long Lake Road & Lahser Road*

The intersection has two lanes of traffic in the east and westbound directions that have a steady amount of residential (non-commercial) traffic during the daytime hours. The north and southbound directions on Lahser Road have only one lane of traffic in each direction, and slower, sparser traffic than Long Lake. Trees encircle the intersection and block line-of-sight in at least one -- if not all -- directions depending upon the position of the RSU. The RSU was placed on the southeastern corner for safety reasons. Northbound and eastbound traffic was nearly atop the RSU by the time foliage permitted line-of-sight (Figure 40). In the southbound direction, a sharp decline hill prevents line-of-sight to even the traffic light until nearly upon the light. Lost GPS (due to tree cover) does not provide an accurate distance-to-RSU, but line-of-sight to the traffic light becomes available near 150 meters from the intersection center. In all directions of travel, ground level foliage prevented line-of-sight communication (Figures 40 and 41).

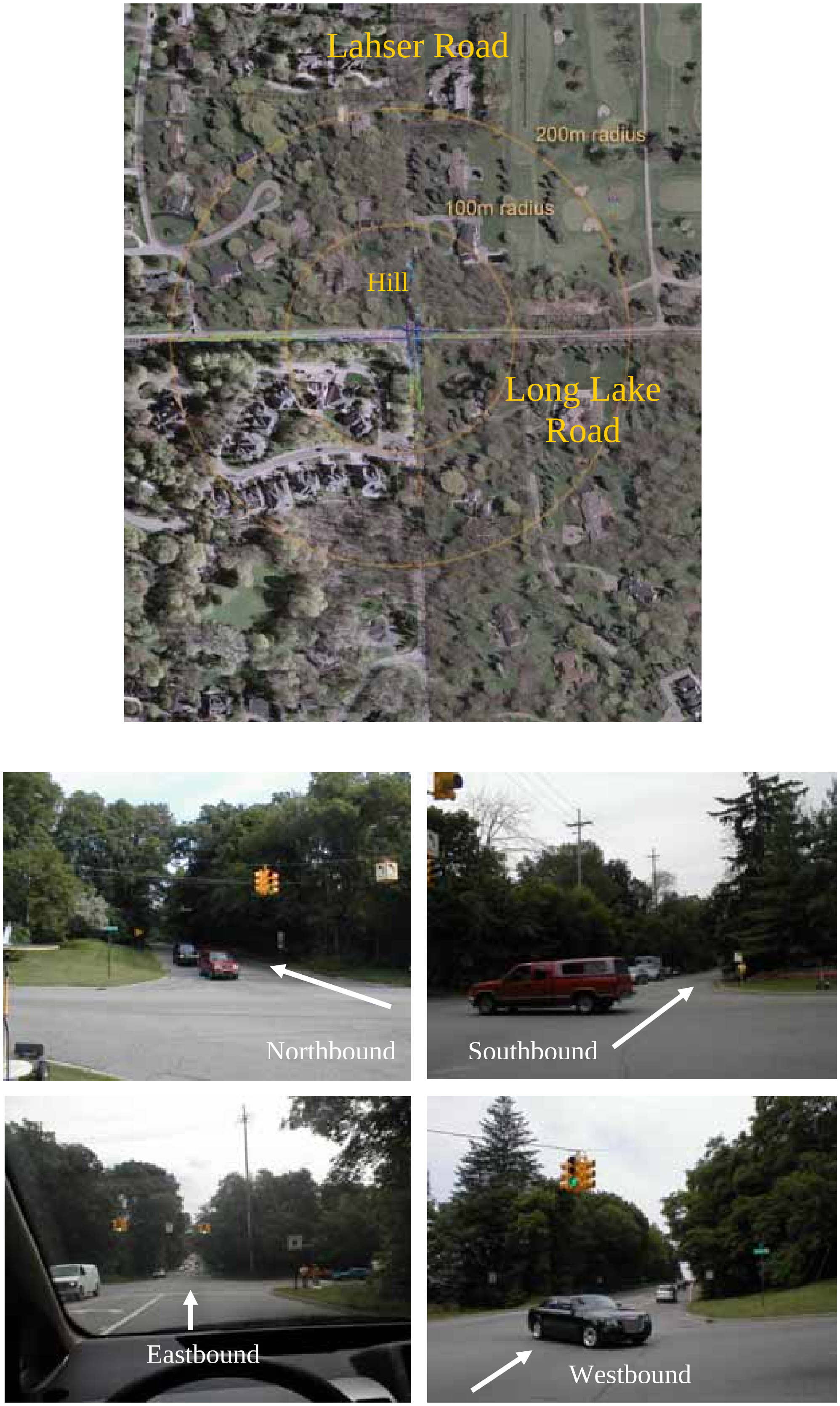



**Figure 40. RSSI Plot and Views for the Long Lake/Lahser Test Route**

For this intersection, the two test personnel stationed at the RSU attempted to identify the first moment that the test vehicle was seen approaching the RSU, and the last moment it was seen driving away from it. These moments in time were linked with the corresponding packet number and identified in the CTK plots of Figure 41 as the estimated periods during which line-of-sight exists between the RSU and the test vehicle.

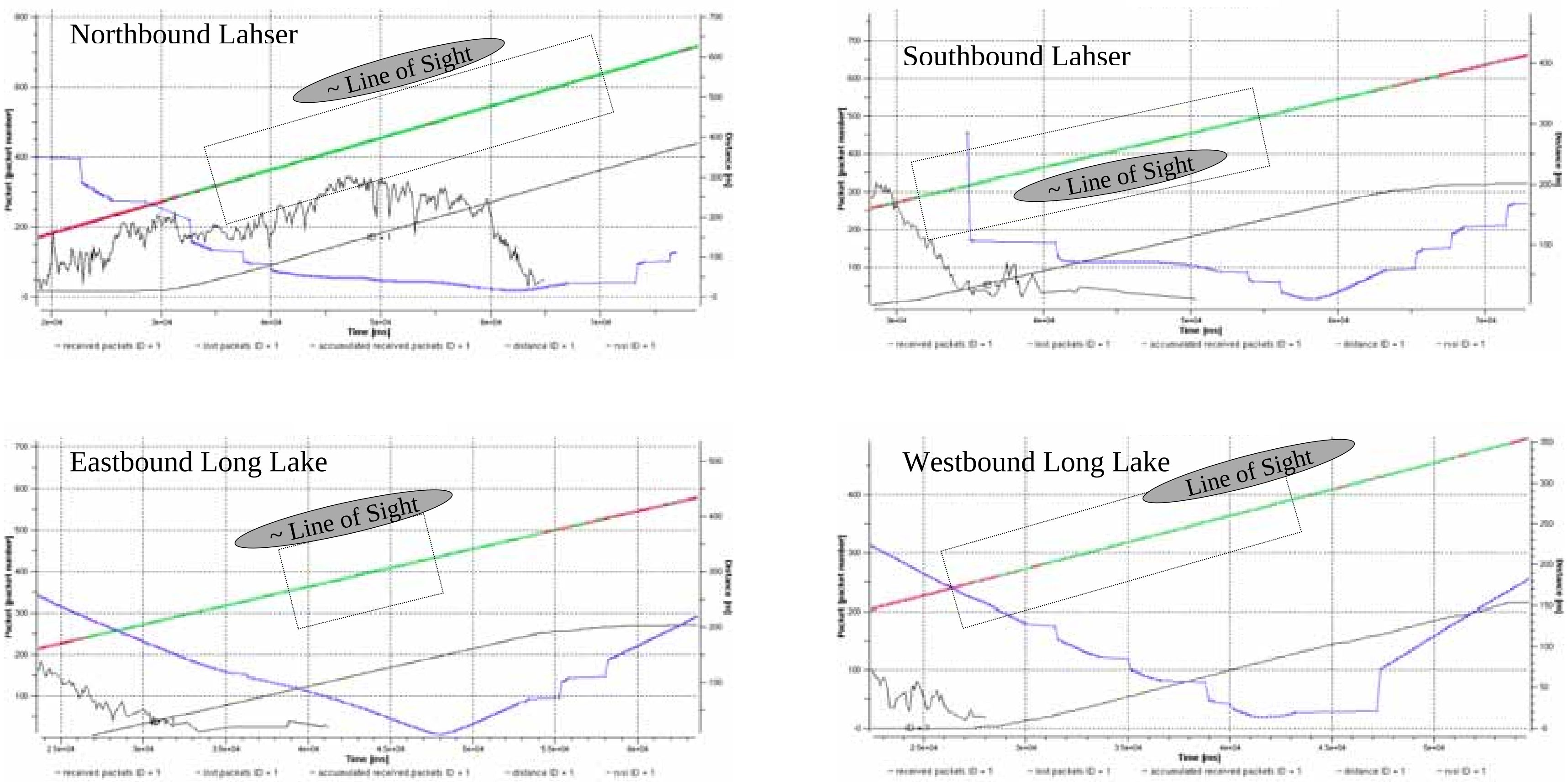



**Figure 41. CTK Plots for the Long Lake/Lahser Intersection**

## *2.1.13 Quarton Road & Lahser Road*

Testing at this intersection was only performed while driving along Quarton Road due to the limited placement choices for the RSU. Aside from left and right turn lanes at the intersection, these roads are limited to one lane of traffic in either direction, and have considerable foliage close to the shoulder of the roads. Quarton rises slightly east of the intersection, cresting a hill about 200m from the RSU. On the west side, the road immediately bends to the south, disappearing from view within about 100m (Figure 42).

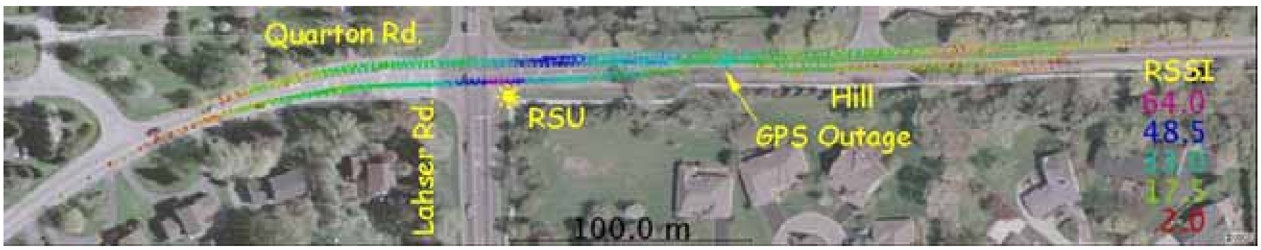



**Figure 42. RSSI Plot for the Quarton Test Route**

Proceeding eastbound, no packets were lost as the test vehicle approached the intersection from within 100 m (Figure 43). Approximately 50m east of the RSU, the GPS signal was temporarily lost due to an obstruction from trees along the road; however, radio reception was not affected in this region. Driving westbound, 2 packets were lost with the test vehicle within ~100m of the intersection in this case. Owing to the slightly different line of sight to the vehicle in the westbound lane, the range of radio reception was slightly different than the prior data, and there were no losses of GPS signal coverage.

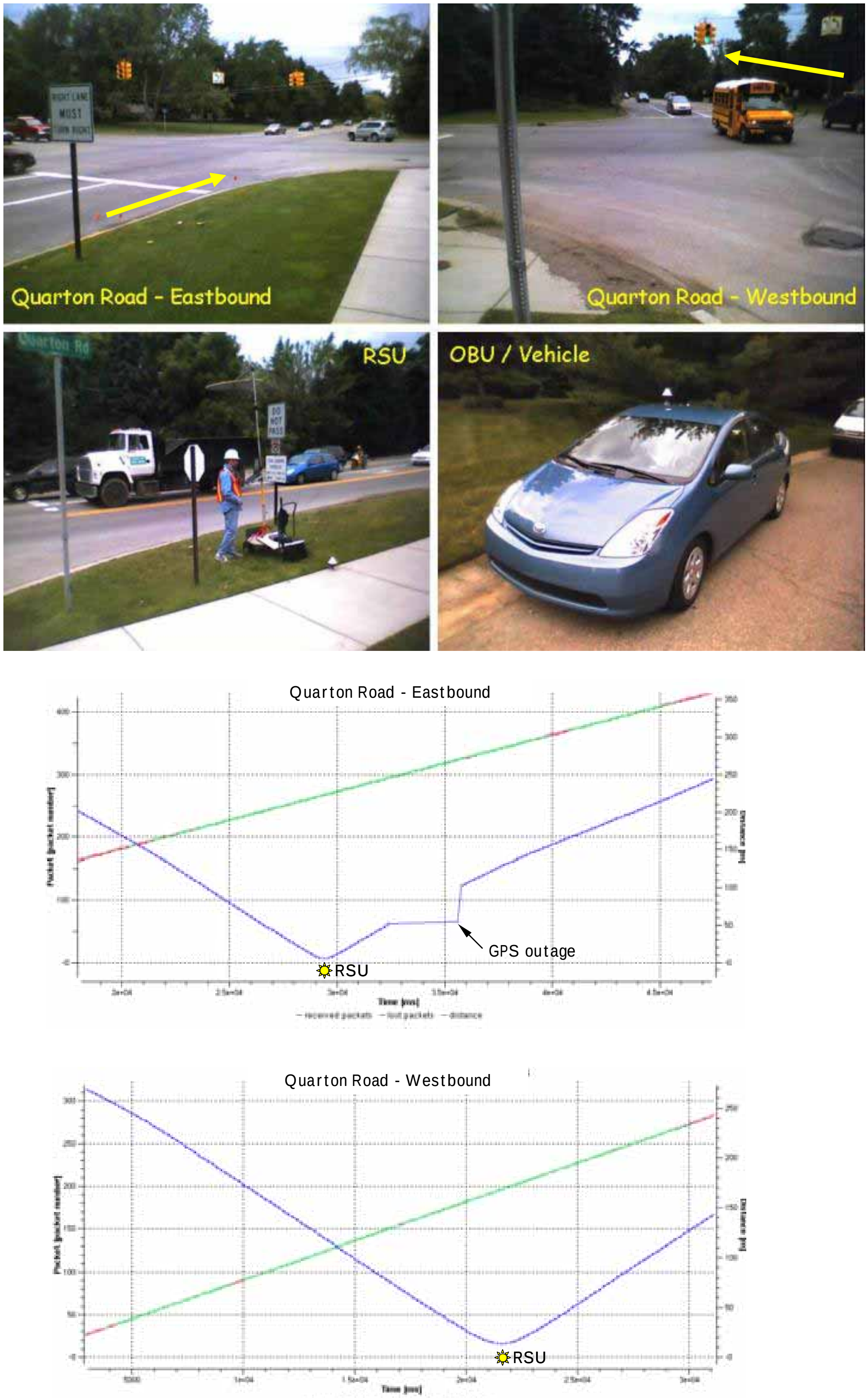



**Figure 43. Views and CTK Plots for the Quarton Test Routes**

### *2.1.14 Skyline Boulevard & Woodside Road*

The intersection of Skyline and Woodside is in the hills area of Redwood City and has light traffic during daytime. Both Skyline and Woodside have a single lane in both directions. Both directions on Skyline away from the intersection have up-hills and the southeastern end is gradually curved to the south. There is dense foliage all over the hills area and surrounding the intersection. There are stop signs on Woodside at the intersection but none on Skyline. The RSU was placed on the western corner to provide line-of-sight to northwest and southeast-bound traffic on Skyline (Figure 44).

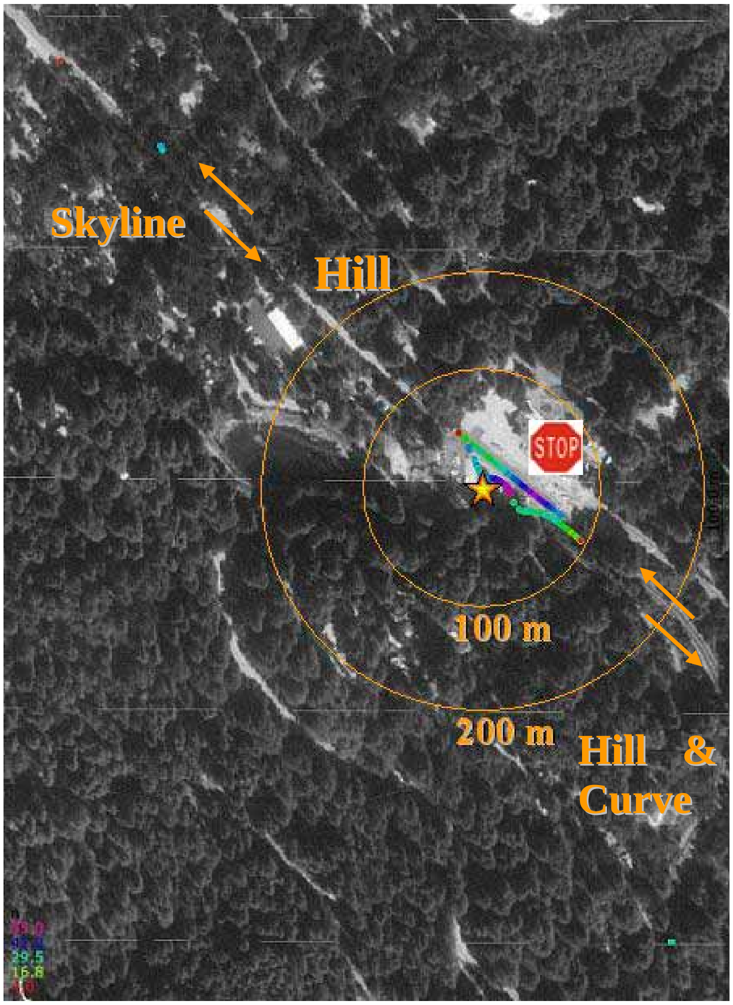



**Figure 44. RSSI Plot for the Sky Line Test Route**

The car started from the RSU and went southeast on Skyline (Figure 45). It turned around, went through the intersection, and turned around again and returned to the RSU. Poor GPS signals and dropped packets were recorded along the test route when the car was more than 70m away from the intersection due to heavy foliage blockage to GPS satellites and no line-of-sight from RSU to OBU at up-hills and curves.

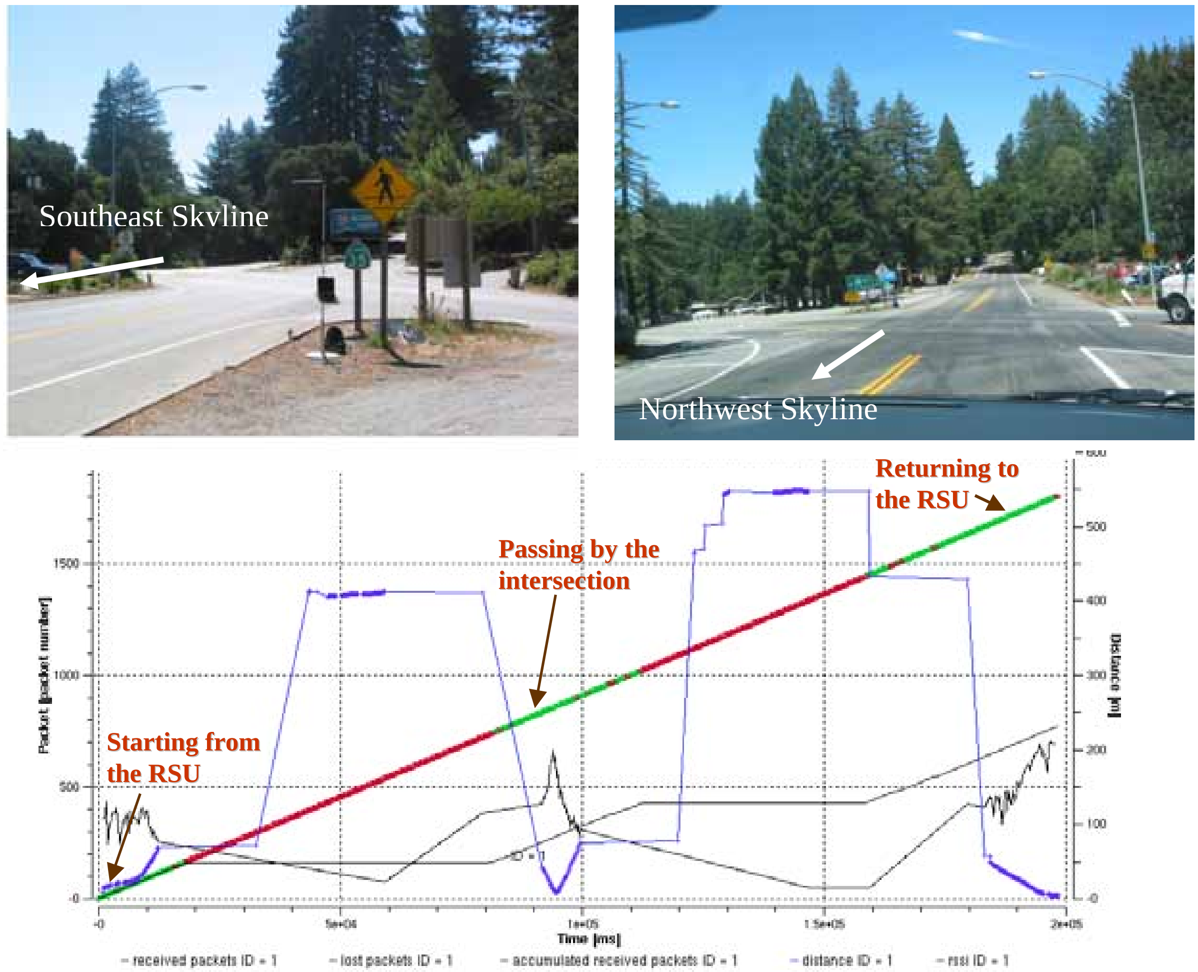



**Figure 45. Views and CTK Plot for the Skyline Test Run**

## *2.1.15 Page Mill Road & Deer Creek Road*

The intersection of Page Mill and Deer Creek in Palo Alto has medium traffic during daytime. Both roads have two lanes at both directions. Southbound Page Mill curves slowly to the southwestern direction and goes uphill. There are trees along the curve. Page Mill has a left turn lane with a traffic light at the Deer Creek intersection. The RSU was placed on the eastern corner since it provided line-of-sight for the southbound and eastbound traffic (Figure 46).

The car started on Page Mill going southbound and uphill. Without line-of-sight, only few or no packets were received. There was 100 percent reception of packets as the car came out of the curve. The car turned left at the light onto Deer Creek going eastbound, and reception was blocked at close to 100m away from RSU due to no line-of-sight (obstructions such as sign posts, controller boxes etc.).

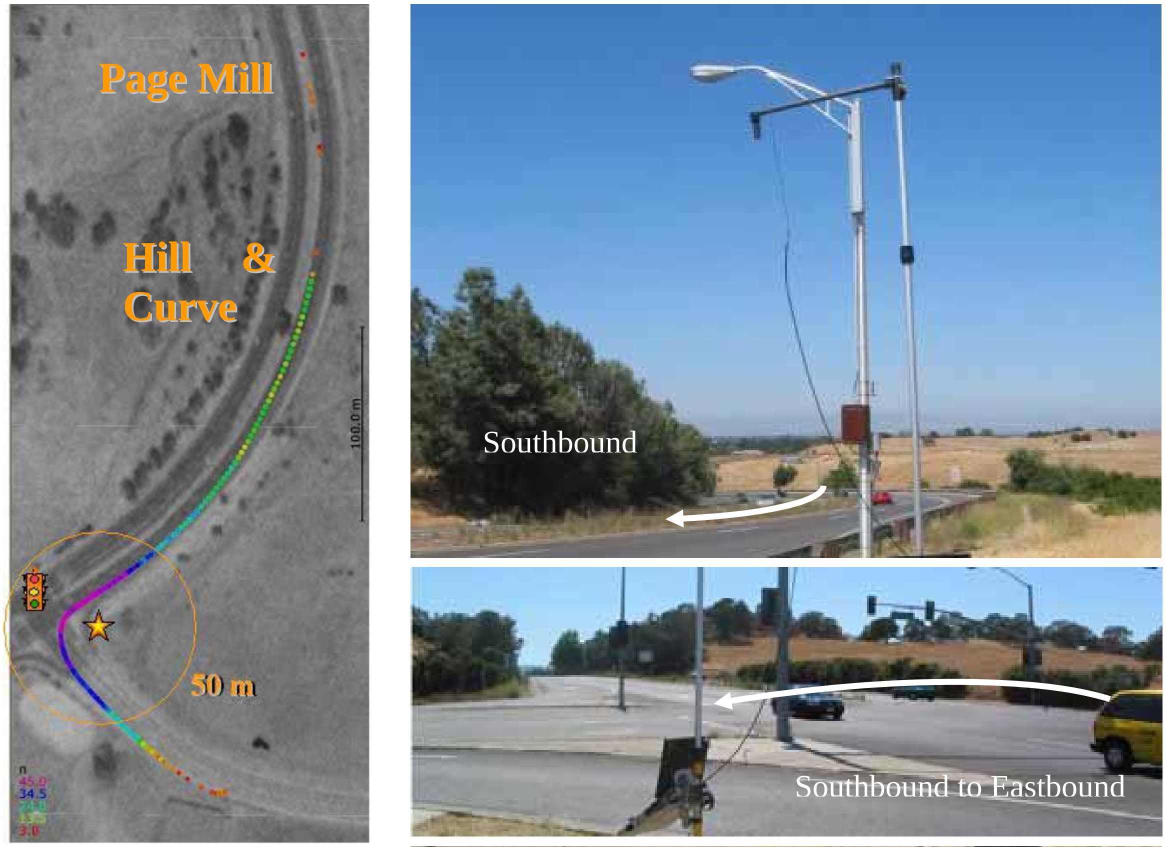



**Figure 46. RSSI Plot and Views for the Page Mill Test Route**

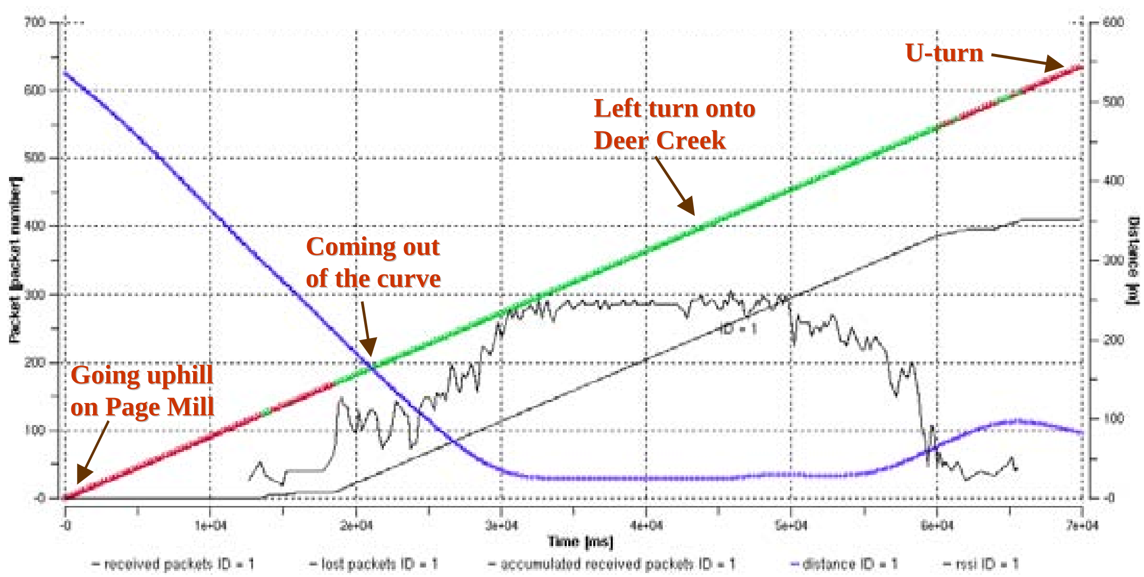



**Figure 47. CTK Plot for the Page Mill Test Run**

### *2.1.16 Squirrel Road & Long Lake Road*

This intersection is characterized by single lane roads, line of sight obstructions, and overhead foliage that often blocked the GPS signal. Vehicles traveling along Squirrel Road experience two hills, both descending southbound, and vehicles traveling along Long Lake Road experience a curving roadway with the line of sight blocked by foliage and terrain along the roadside.

Packet reception for northbound and southbound travel was quickly interrupted by line of sight blockage due to Hills #1 and #2, and GPS outage along this route was prevalent due to thick foliage above the roadway (Figure 48). Packet reception for eastbound and westbound travel faded off gradually beyond 100m due to impeding terrain and foliage along the curving roadway. Infrequent GPS outages occurred due to the trees overhead.

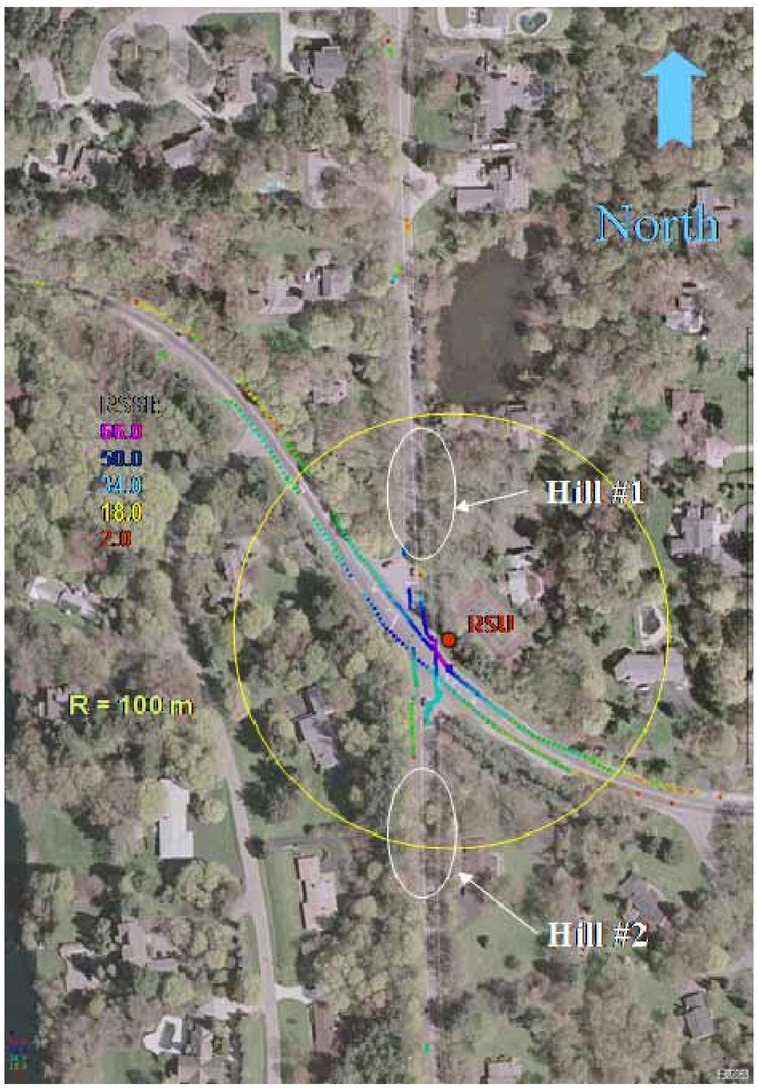



**Figure 48. RSSI Plot for the Squirrel and Long Lake Test Routes**

For Squirrel Road northbound, initially packets were lost due to blockage when the test vehicle was driving up Hill #2 and/or foliage alongside the roadway (Figure 49, caption 1). The GPS signal was often blocked by overhead foliage. The vehicle stopped before the red light 20 meters from the RSU with 100 percent packet reception rate (2). Packet reception was interrupted after driving over Hill #1 on Squirrel Road (3). The GPS signal was blocked by overhead foliage.

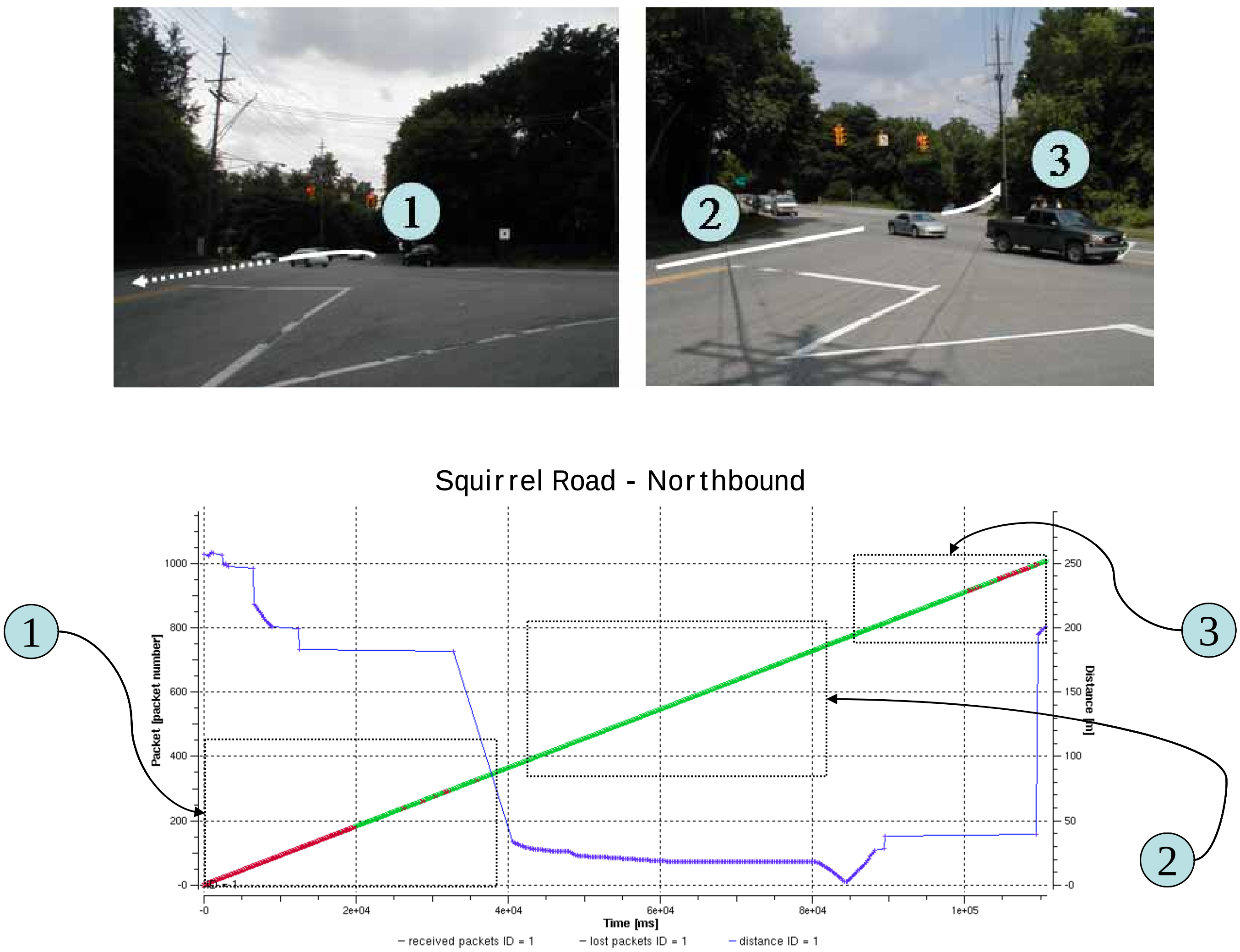
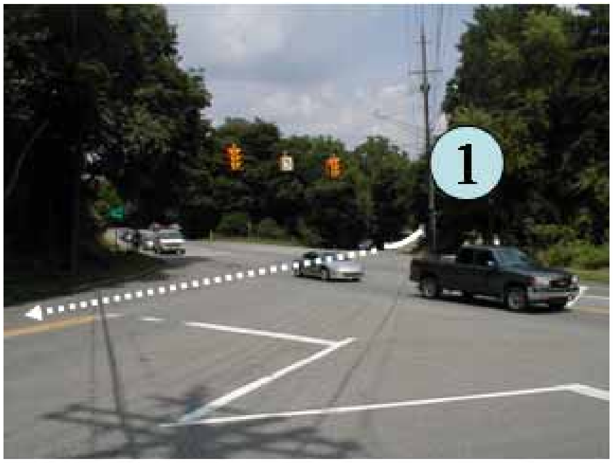
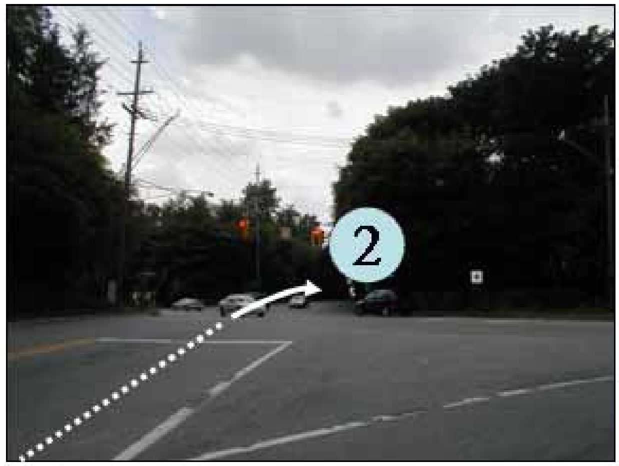



**Figure 49. Views and CTK Plot for Northbound Squirrel Test Run**

For Squirrel Road southbound, packet reception was initially blocked by Hill #1 and/or foliage along the roadside (Figure 50, caption 1). The GPS signal was blocked by overhead foliage. At the intersection, packet reception was excellent until the test vehicle passed over Hill #2, while the overhead foliage again blocked the GPS signal (2).



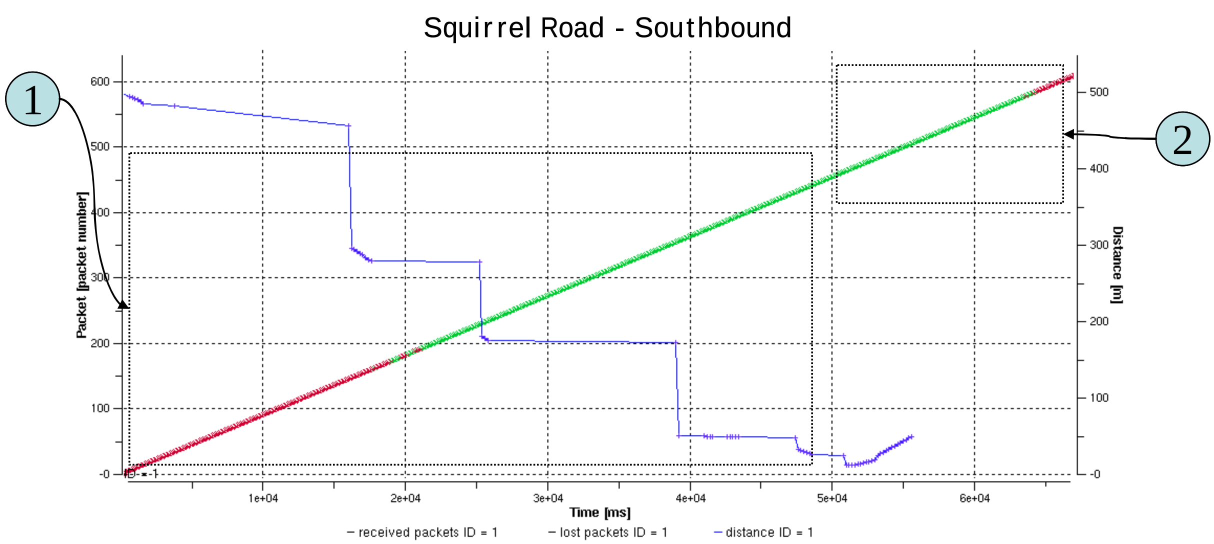
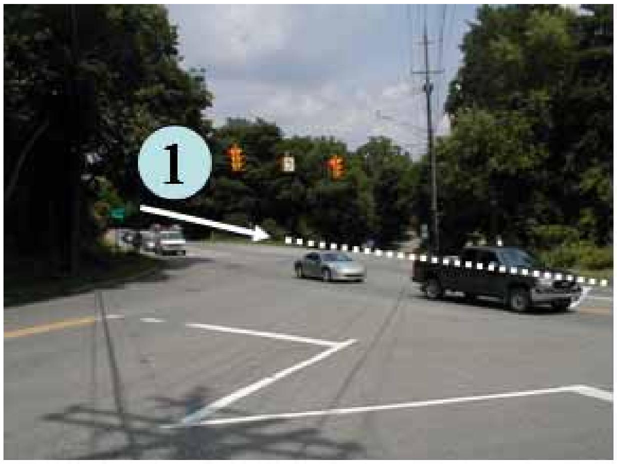




**Figure 50. Views and CTK Plot for the Southbound Squirrel Test Run**

For westbound Long Lake, line of sight was initially blocked by terrain and foliage along the curving roadway before packet reception becomes 100 percent as the vehicle approached from ~100 m (Figure 51, caption 1). The test vehicle stopped at the traffic signal with 100 percent packet reception (2). Intermittent packet reception and GPS outage occurred as the vehicle traveled along the curving roadway with foliage and terrain blockage (3).


**Figure 51. Views and CTK Plot for the Westbound Long Lake Test Run**

For eastbound Long Lake, the line of sight was initially blocked by terrain and foliage along the curving roadway before packet reception became 100 percent as the vehicle approached from ~100 m (Figure 52, caption 1). Intermittent packet reception and GPS outage occurred as the vehicle traveled along the curving roadway with foliage and terrain blockage (2).





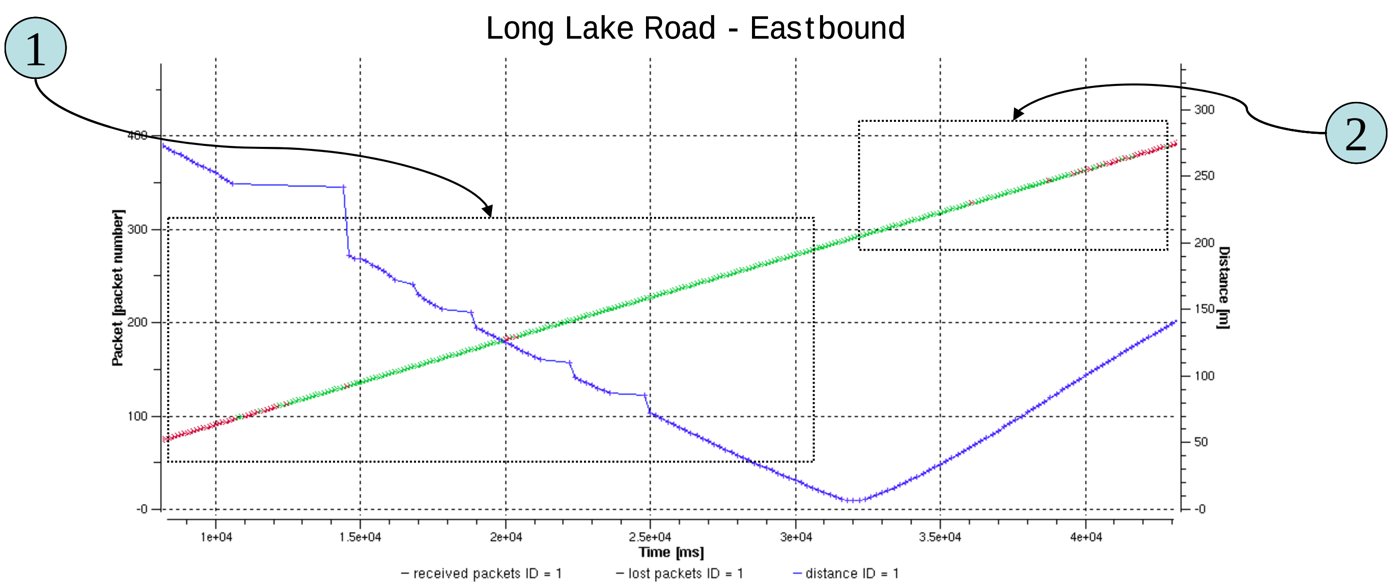



**Figure 52. Views and CTK Plot for the Eastbound Long Lake Test Run**

## 2.2 Comparisons with the Open Environment Baseline Data

Figure 53 shows the Received Signal Strength Indicator (RSSI) data from two locations superimposed. Testing at the intersection of Oakwood Boulevard and Michigan Avenue in Dearborn is superimposed upon the corresponding data acquired from the Milford Proving Grounds (MPG). To somewhat simplify the graph, data south and west of the RSU have been arbitrarily plotted on the negative axis, while data north and east of the RSU have been plotted on the positive axis.

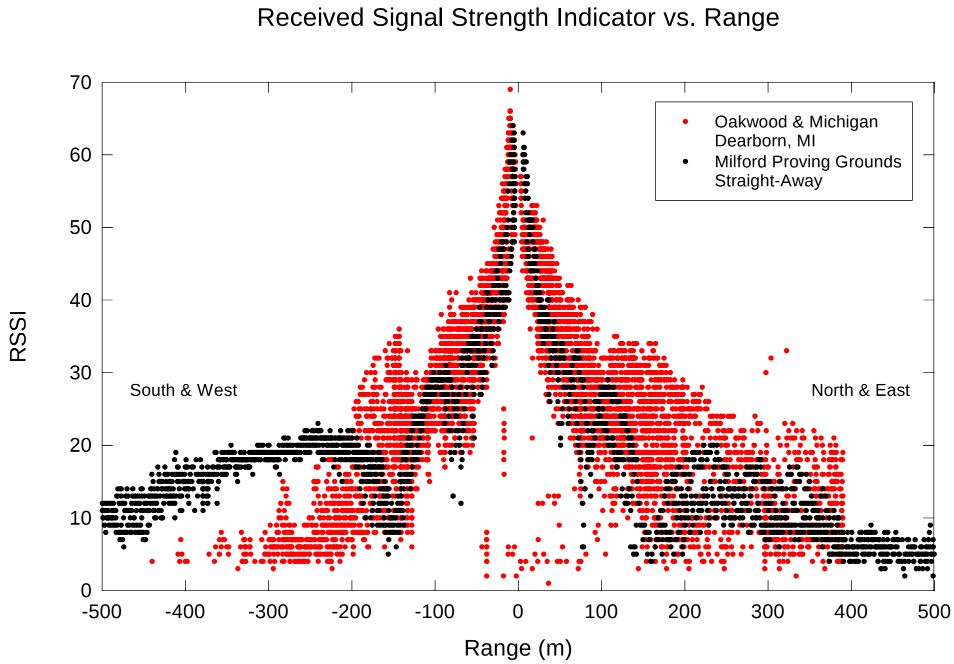



**Figure 53. Data Comparison of Oakwood/Michigan and Milford Proving Grounds**

There are several interesting observations to gather from this plot. The testing environment at the Oakwood and Michigan intersection is quite cluttered, both with buildings and other physical obstructions and also with very dense traffic. Despite this, over the range corresponding to line of sight between the RSU and OBU, the RSSI with distance displays essentially the same envelope with distance as that measured at the more wide open environment found at the MPG. We also observe that the nulls in the MPG data at ~75m and ~150m are not observed in the intersection testing data, presumably due to the multitude of multipath reflections created by the dense environment. Finally, there is also a much greater variability in the RSSI at a given distance in the intersection testing data, again likely due to the dense environment.

Figure 54 shows the RSSI data from the intersection of Crooks and Big Beaver Roads in Troy plotted along with the corresponding data acquired from the Milford Proving Grounds. The plots have been derived from multiple sets of runs - in the case of the intersection at Crooks and Big Beaver, 12 data sets were combined, binned into histograms of 10m intervals, and the mean RSSI values calculated. For the MPG data, four runs were compiled.

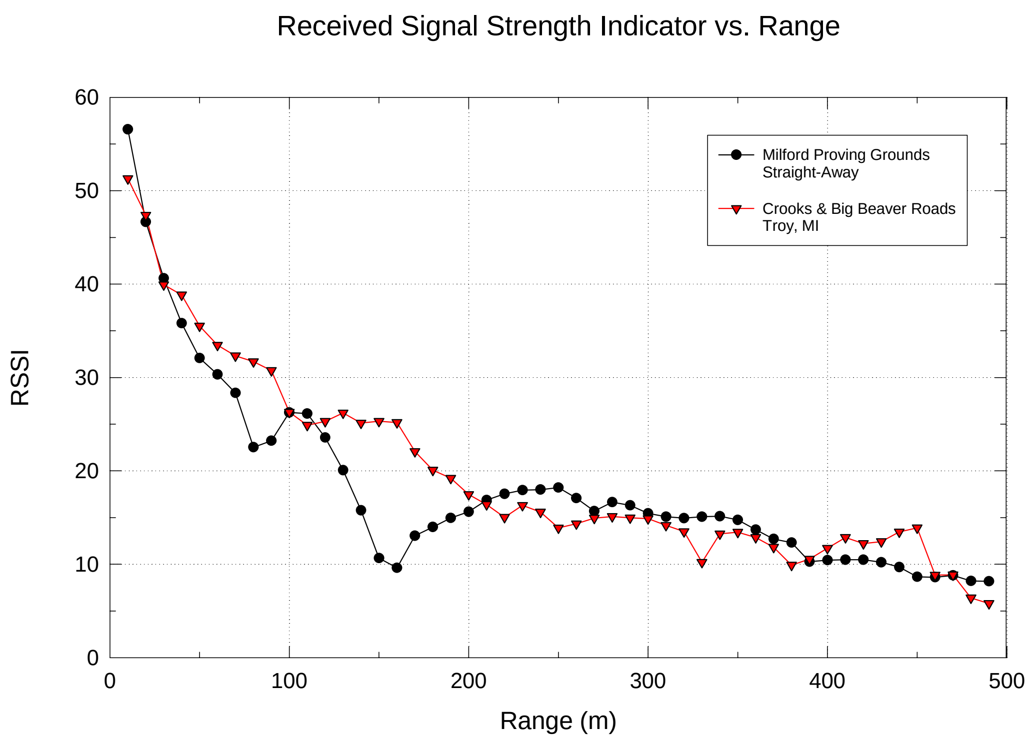



**Figure 54. Data Comparison of Crooks/Big Beaver and Milford Proving Grounds**

Note that the intersection at Crooks and Big Beaver is far less cluttered than the Oakwood and Michigan intersection described in the previous figure. However, as with the previous case, the key points to note are that the nulls in the MPG data at ~75m and ~150m are clearly not present in the data from the intersection testing, and that the overall shape of the RSSI with distance is the same for both the intersection and MPG testing scenarios. (Although error bars were not shown on the graph to maintain clarity, the spread in data about the mean was again far larger for the intersection scenario than for testing at MPG.) These results suggest that obstructions found in the typical intersection environment do not noticeably degrade the quality of radio reception.

## 2.3 Summary

Intersections in the Detroit and San Francisco Bay areas were chosen as sites for DSRC transmission characterization in order to gain a better understanding of how the unique characteristics of these intersections affect DSRC communications. All intersection testing was conducted with prior approval from the public jurisdictions responsible for the intersections. The Consortium used the Task 4 CTKs and the Task 6C antennas as improvised roadside units.

- Though not optimized for the functionality that would be expected of an RSU, the Task 4 CTKs and Task 6C antennas provided more than adequate range as demonstrated in the baseline evaluation conducted at Milford Proving Grounds (MPG). Packets were received when the test vehicle was more than 500m from the RSU, and this is well in excess of anticipated range requirements for in-vehicle safety applications.

- Open environment testing conducted at MPG also revealed that there are local minima in the RSSI at ranges corresponding to ~75m and ~150m, consistent with results found and reported in the Task 4 Report (Multipath Considerations) regarding the geometry of the radio propagation for our testing arrangement.

- All intersection testing was conducted with a single RSU broadcasting to an OBU-equipped test vehicle traveling through the thoroughfare. The effect of many OBUs attempting to transmit at the same time as the RSU is addressed in the Task 12 Simulation Report.

- The general findings from testing conducted at a representative intersection (Woodward Avenue and I-696 Service Drive in Huntington Woods, Michigan) demonstrate an 85 percent successful transmission ratio while the test vehicle was approaching the RSU from 250 m, and a 99 percent success ratio while approaching from 100m.

- In some cases, packet reception near an intersection can be blocked by heavy vehicle traffic. This situation can likely be improved upon by changing the positioning of the RSU that was used during our testing (~10’ height, etc.) so that the line-of-sight is optimized. It is likely that RSU positioning will not resolve all line-of-sight blockages between RSU and OBU antennas, especially for vehicles that are traveling behind large trucks, and this fact should be taken into consideration when designing intersection-based safety applications.

- In some cases, reception was maintained despite the fact that there was no line-of-sight between the antennas. But eventually packet reception was lost in those situations when the test vehicle moved further and further away from the RSU around a bend in the road with significant terrain and foliage blocking the view between the antennas.

- As expected, reducing the power level of the DSRC sending unit decreases the range at which packets can be received. This can be an important consideration when specifying RSU output levels.

- Downhill grades and extensive foliage can block the line-of-sight of vehicles approaching an intersection, up to the point where they are almost upon the cross street. A method of providing the RSU transmissions to these vehicles, be it through infrastructure-based repeaters or by other means, should be considered for safety critical systems.

- There were many instances when the GPS signal was lost, but packet reception between the RSU and the OBU was maintained, especially in locations near tall buildings or under extensive foliage. The prospect of maintaining adequate vehicle positioning resolution under concrete canyon or tree-laden conditions is a design issue for intersection safety system development.

- Comparing typical intersection data with similar data from the more wide-open environment found at MPG, the RSSI with distance displays essentially the same envelope. We also observed that the nulls in the MPG data at ~75m and ~150m are not observed in the intersection testing data, presumably because of multipath reflections created by the dense environment, and variability of the geometries involved during subsequent test runs. It was also noted that there is also a much greater variability in the RSSI at a given distance in the intersection testing data, again likely due to the dense environment.

# 3 INTERSECTION TESTING USING A SYNCHRONIZED TRAFFIC CONTROLLER

In this section the results of the testing at the Orchard Lake & 10 Mile Roads intersection are discussed and analyzed. In contrast with previous testing at various locations around the Detroit and Palo Alto areas, some of the new elements introduced for this particular intersection were:

1. Wave Radio Modules (WRM) and Task 9 Laptop were used instead of Task 4 CTKs.
2. RSU wireless message consisted of actual traffic signal controller data (phase & timing) instead of "dummy" packets.
3. All radios were configured in both transmit and receive modes, therefore the RSU was also receiving the actual dynamic data from the OBU (vehicle speed, location, etc.).

## 3.1 Background and Test Set-Up

Due to logistical and safety concerns, it was decided that rather than connecting the Task 9 laptop to the traffic signal controller actually controlling the traffic lights it would be connected to a second, independent controller. This second controller was programmed with exactly the same timing as the actual controller but its outputs were not connected to any traffic lights. There were several reasons for this decision:

- To eliminate any risk of interfering with the intersection traffic controller.
- To be less dependent on the local authorities for support than if we were connecting directly to intersection traffic signal controller.
- To be immune from any potential incompatibilities with the traffic signal controller installed at the intersection.

The controller used was an Eagle EPAC300 M30. It is shown in Figure 55.


**Figure 55. EPAC M30**

### *3.1.1 Traffic Signal Controller Interface*

Getting the traffic signal information from the controller into the Task 9 laptop proved to be much more difficult than first anticipated. Real-time transmission of the current state of the traffic lights and the countdown to the next state are generally not a feature on most controllers.

Fortunately, with some assistance from Virginia Tech, the RS-232 output from the Eagle controller was able to be requested and read through an experimental interface. This traffic signal controller output is primarily intended to communicate with other devices running Eagle software and is not well documented. The experimental traffic signal controller interface was implemented in the Task 9 software.

Using the data received from the traffic signal controller the Task 9 software was then able to transmit the traffic signal information wirelessly. The content of the RSU message is summarized (in a simplified manner) in Table 9. More details on the RSU serial interface and message format can be found in the Appendix F.

| | | |
|---|---|---|
| *RSU Header Message* | *Message Type* | *1 byte* |
| | *RSU I.D* | *6 bytes* |
| | *Precision indicator* | *1 byte* |
| | *Latitude, Longitude, Altitude of RSU* | *11 bytes* |
| | *UTC Time* | *5 bytes* |
| *Traffic Controller Data* | *Latitude, Longitude, Altitude of Stop. Loc. #1* | *11 bytes* |
| | *Directionality of Stop. Loc. #1* | *2 bytes* |
| | *Current State of Traffic Light at Stop. Loc. #1 (Green, Yellow, Red)* | *1 byte* |
| | *Time left in current state of Traffic Light at Stop. Loc. #1* | *2 bytes* |
| | *Duration of Yellow State at Stop. Loc. #1* | *2 bytes* |
| | …… | … |
| | *Latitude, Longitude, Altitude of Stop. Loc. #4* | *11 bytes* |
| | *Directionality of Stop. Loc. #4* | *2 bytes* |
| | Current State of Traffic Light at Stop. Loc. #4 (Green, Yellow, Red) | 1 byte |
| | *Time left in current state of Traffic Light at Stop. Loc. #4* | *2 bytes* |
| | *Duration of Yellow State at Stop. Loc. #4* | *2 bytes* |

**Table 9. RSU message**

### 3.1.2 *Choice of Intersection*

The intersection chosen for the test was Orchard Lake Road and 10 Mile Road in Farmington, Michigan. This intersection was chosen for several reasons:

- The timing of the lights is constant, i.e. there are no traffic flow sensors that cause the timing of the lights to be dynamically adapted.

- The traffic signal controller and lights installed at the intersection are owned and maintained by the Road Commission for Oakland County (RCOC) and earlier contact between VSCC and RCOC seemed to indicate the best potential for successful cooperation.

- It is reasonably close to the CAMP facility in Farmington Hills and therefore requires less logistical efforts that other intersection.

Figures 56 through 59 show the intersection from four different directions.


**Figure 56. Orchard Lake Road – Southbound Direction**

**Figure 57.  10 Mile Road – Eastbound Direction**

**Figure 58.  Orchard Lake Road – Northbound Direction**

**Figure 59. 10 Mile Road – Westbound Direction**

### *3.1.3 Test Preparations*

The independent traffic signal controller was programmed by the Road Commission for Oakland County (RCOC) to use exactly the same timing as the controller at the selected intersection (10 Mile Road and Orchard Lake Road). Specifically, the program was a fixed 70-second cycle broken down as follows:

- 28 seconds of green for Orchard Lake Road
- 5 seconds of yellow for Orchard Lake Road
- 1 second of red for all directions
- 36 second of red for Orchard Lake Road
- 30 seconds of green for 10 Mile Road
- 5 seconds of yellow for 10 Mile Road
- 1 second of red for all directions
- 34 seconds of red for 10 Mile Road

On the day of testing, the synchronization of the clocks on both controllers (the independent controller and the one installed and controlling the traffic lights at the intersection) was achieved with the assistance of a technician from RCOC. This synchronization had the effect of "matching" the timing programs in each controller and thus in theory both controllers were operating in parallel.

This synchronization of the controllers was verified in three ways:

1. Visually comparing the traffic light display on our controller with the state of the lights in the intersection.

2. Visually comparing the traffic light display in the Task 9 software with the state of the lights in the intersection.

3. Later in post-processing time-stamped video of the state of the lights was compared to the time-stamped output of our controller collected by the Task 9 software. They were found to be within 100 to 200 milliseconds of one another.

It is worth noting that after about an hour of testing, the two controllers were slightly out of synchronization. The controller connected to the RSU was lagging behind the installed controller. Later, it was determined that the power supply being used (an inverter running off a vehicle's 12 VDC power) to power the independent controller caused the clock to run slow. It lost about a millisecond every second. This was a steady drift and was corrected for in the data analysis.

For all the tests the RSU equipment was set up and transmitting from the southeast corner of the intersection. Also, the WRMs were configured to send and receive on the DSRC Control Channel, which is Channel 178 with a center frequency of 5890 MHz and a 10 MHz bandwidth.

## 3.2 Full Power Transmit Testing and 5.9 GHz DSRC Intersection Characterization

The first set of tests consisted of transmission of the RSU message Table 9 with the following WRM configuration:

| Packet Length (bytes) | Message Interval (ms) | Data Rate (Mbps) | Transmit Power (dBm) |
|---|---|---|---|
| 500 | 100 | 6 | Full (~20 dBm) |

**Table 10. WRM configuration for RSU message (Full dBm)**

Testing consisted of driving through the intersection in every direction and in every lane at normal traffic speeds. The RSU message received by the WRM-OBU in the vehicle was logged along with synchronized (GPS time stamp) video for post processing.

### *3.2.1 Performance Characterization*

To assess the performance of the 5.9 DSRC technology and the WRMs in particular, the intersection data from all the runs was analyzed by calculating the ratio of received versus sent packets. It is important to note that this ratio was derived by initially considering the first and last received packet regardless of where the receptions occurred. Later on in the next section, another calculation of the successful transmission ration was performed to provide a more relevant reception percentage in the range of interest (250 m for the traffic signal violation warning application).

The summary plots depicting received packets, range from the RSU and RSSI for representative runs in every direction can be found in Figures 60 through 63. The range of communication achieved at full power setting (~20dBm) varied between 400 and 600 m. For the full range of communication, the successful transmission percentage was between 85 percent and 95 percent in all directions except for the northbound leg of the intersection where it dropped to 69 percent. In the Northbound direction (see Figure 63) a large number of packets were lost at ranges beyond 500m and this contributed to the lower ratio of 69 percent. The sporadic reception of packets at ranges beyond 500 m, which can dramatically reduce the successful transmission ratio, highlights the need to limit the range of interest when analyzing the data. In this case, the range of interest is approximately 250 m as defined by most safety applications in Task 3. Figures 64 through 71 summarized the results when the range of interest is limited to 250 m. The successful transmission ratio varies between 88 percent and 96 percent.

The communication outages experienced during testing were mainly of minimal duration (200 ms; i.e., one packet lost then communication is re-established). Longer outages of approximately one second in the eastbound and northbound data warranted a closer look and some justification. In the eastbound direction, an examination of the video collected during these runs, and the digital photographs documenting the RSU set-up, revealed that the likely cause of the repeatable one-second outage was due to a road sign obstruction of the transmitting antenna. This situation would not occur if a more optimal set-up of the antenna (high in the middle of the intersection, for example) were logistically feasible during our testing. In the northbound direction, the longer outages occurred, as expected, around the 250 m range in a hilly part of the roadway.

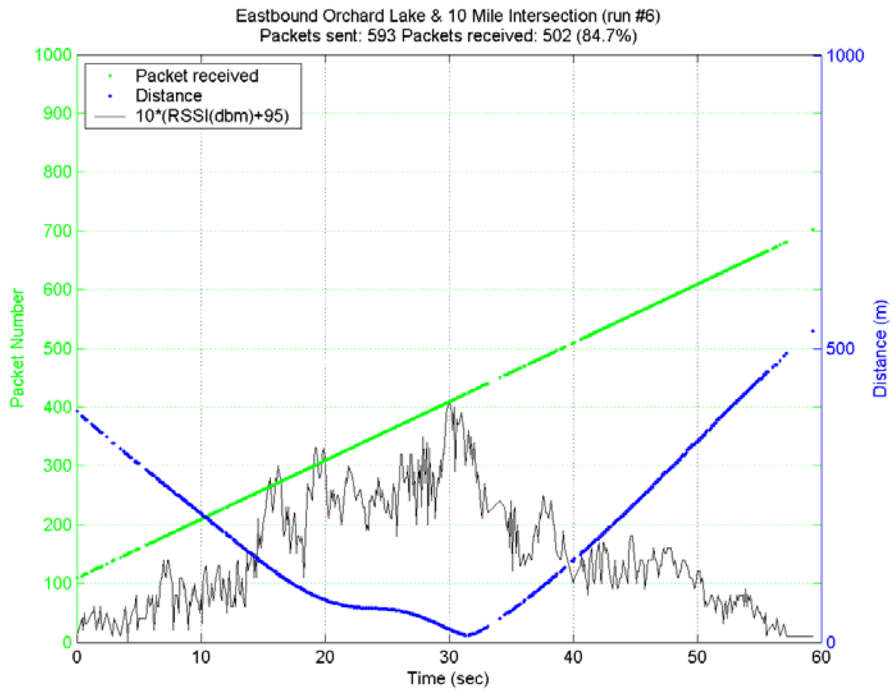



**Figure 60. Eastbound 10 Mile Rd. Packets Received, Range, and RSSI**

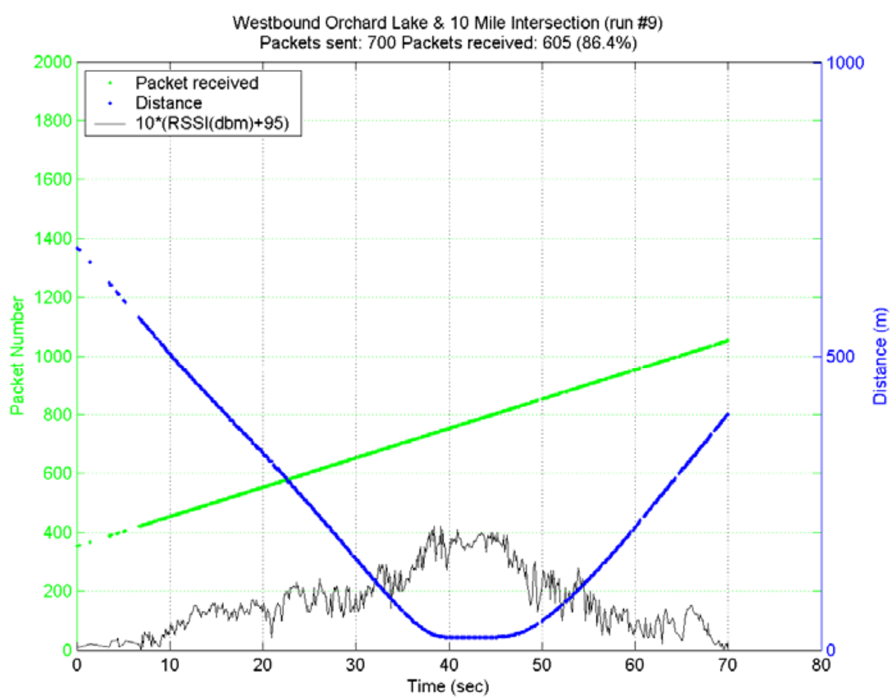



**Figure 61. Westbound 10 Mile Rd. Packets Received, Range, and RSSI**

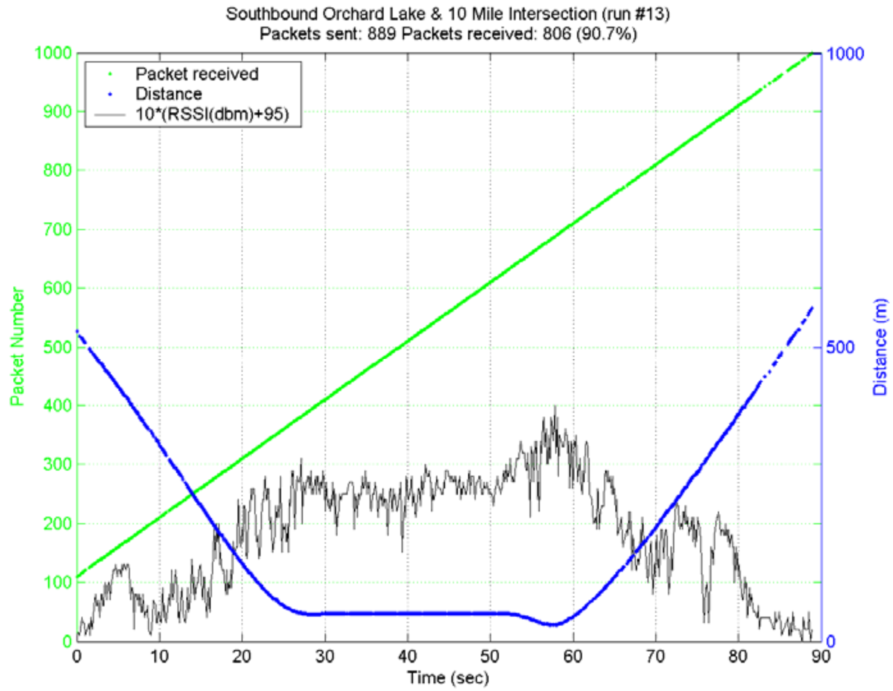



**Figure 62. Southbound Orchard Lake. Packets Received, Range, and RSSI**

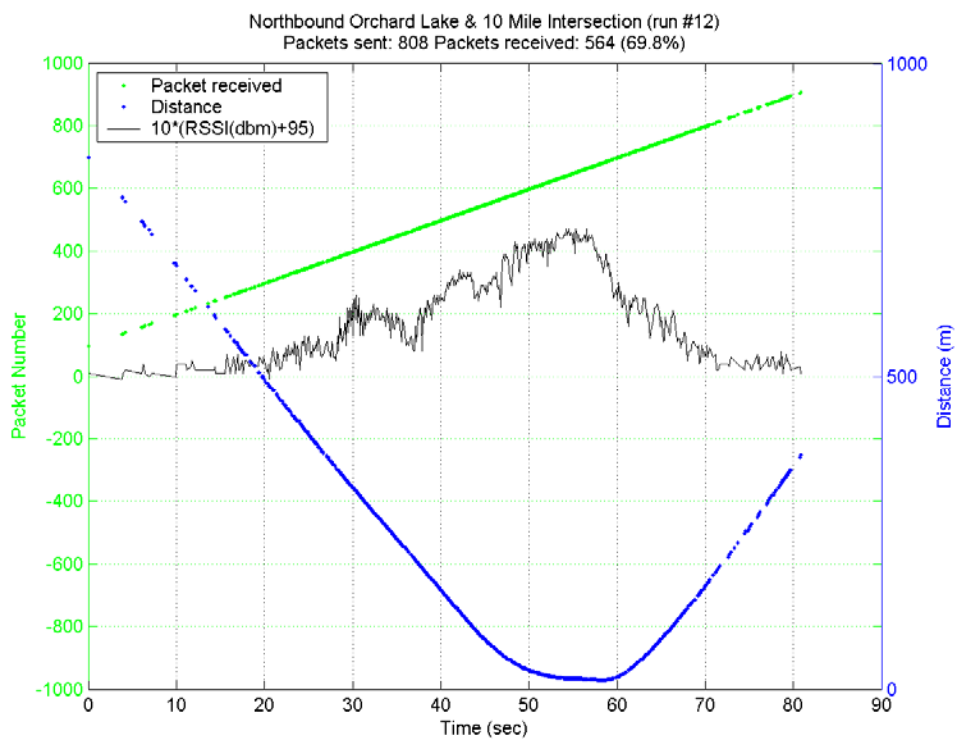



**Figure 63. Northbound Orchard Lake. Packets Received, Range, and RSSI**

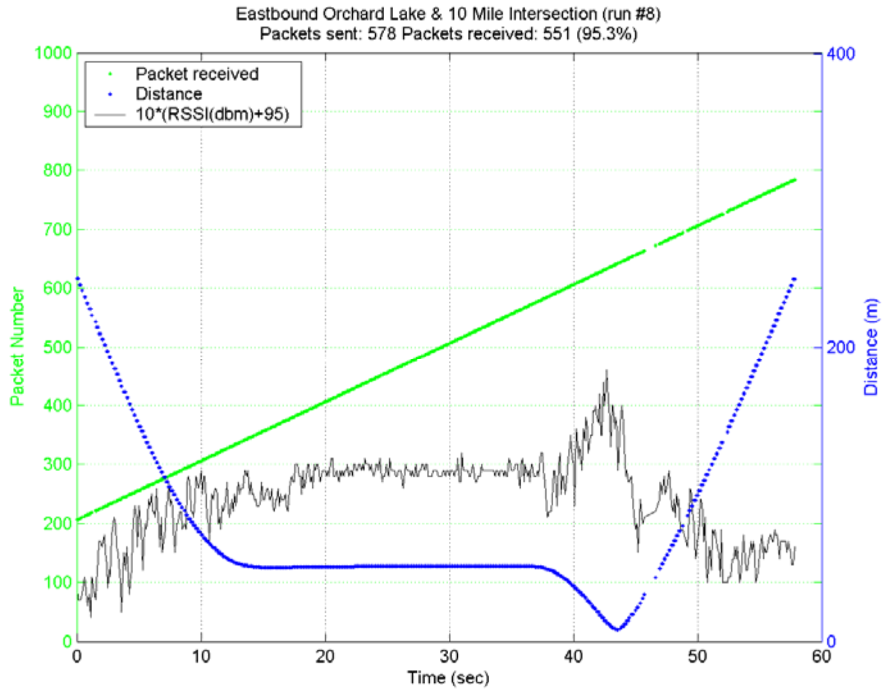



**Figure 64. Eastbound 10 Mile Rd. Packets Received, Range, and RSSI Within 250 m Range of Interest for Safety Applications**

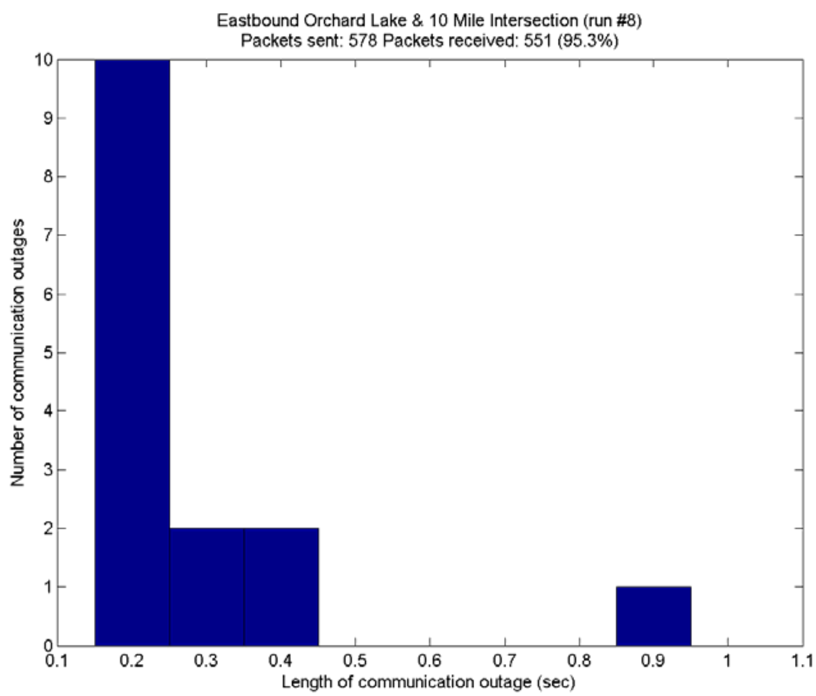



**Figure 65. Number of Outages and Length in Eastbound Direction Within 250 m**

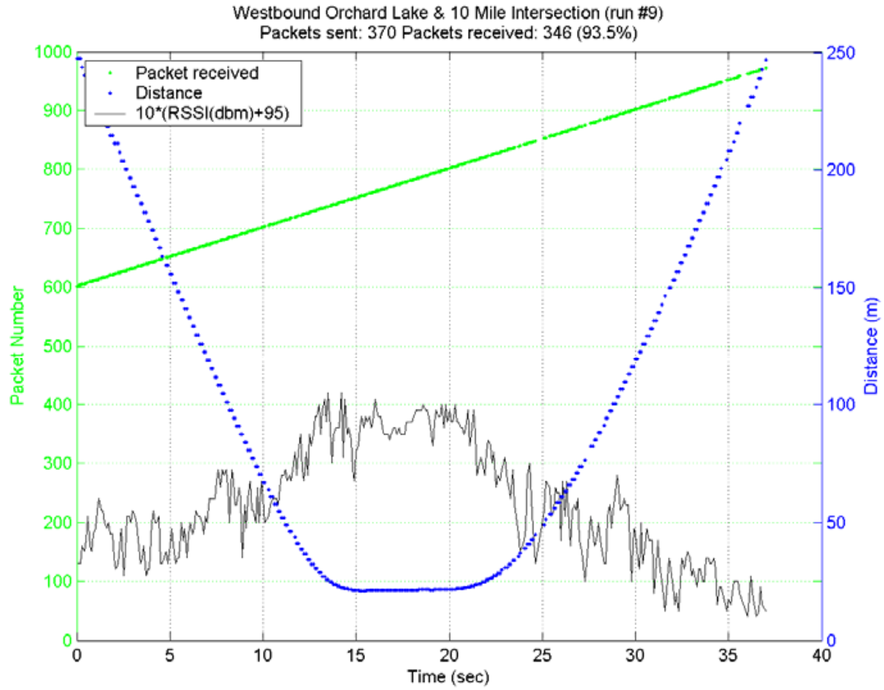



**Figure 66. Westbound 10 Mile Rd. Packets Received, Range, and RSSI Within 250 m Range of Interest for Safety Applications**

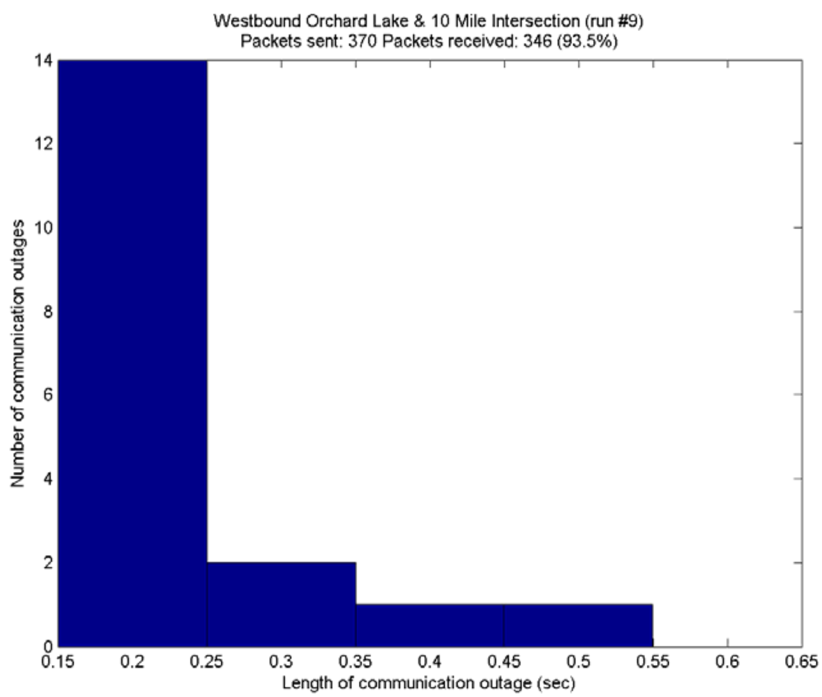



**Figure 67. Number of Outages and Length in Westbound Direction Within 250 m**

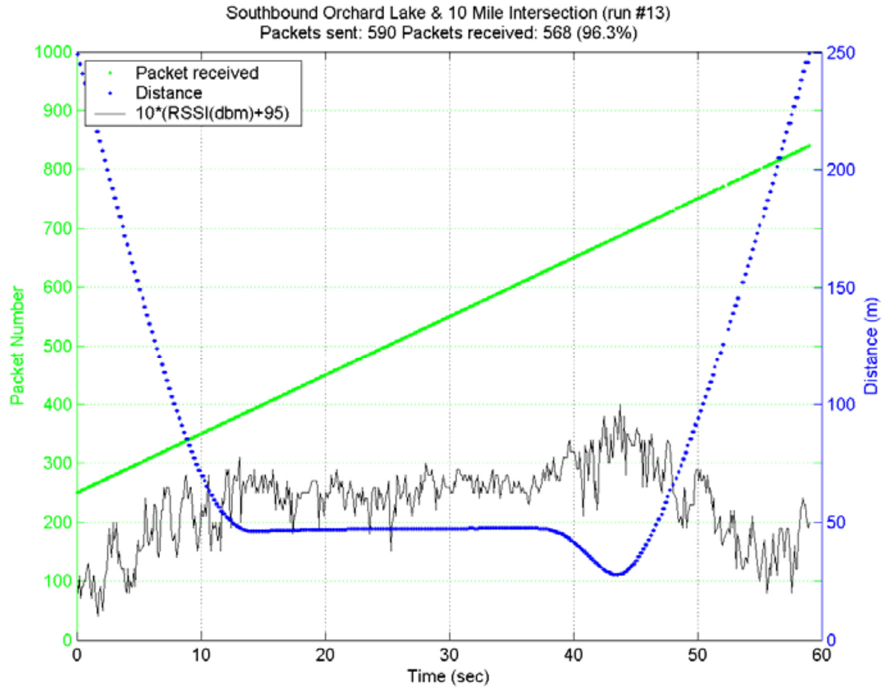



**Figure 68. Southbound 10 Mile Rd. Packets Received, Range, and RSSI Within 250 m Range of Interest for Safety Applications**

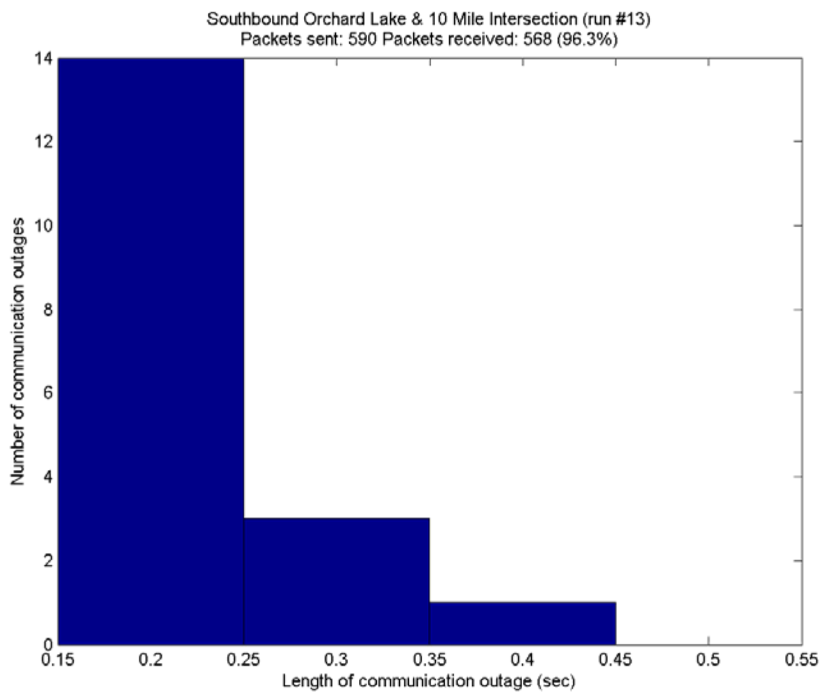



**Figure 69. Number of Outages and Length in Southbound Direction Within 250 m**

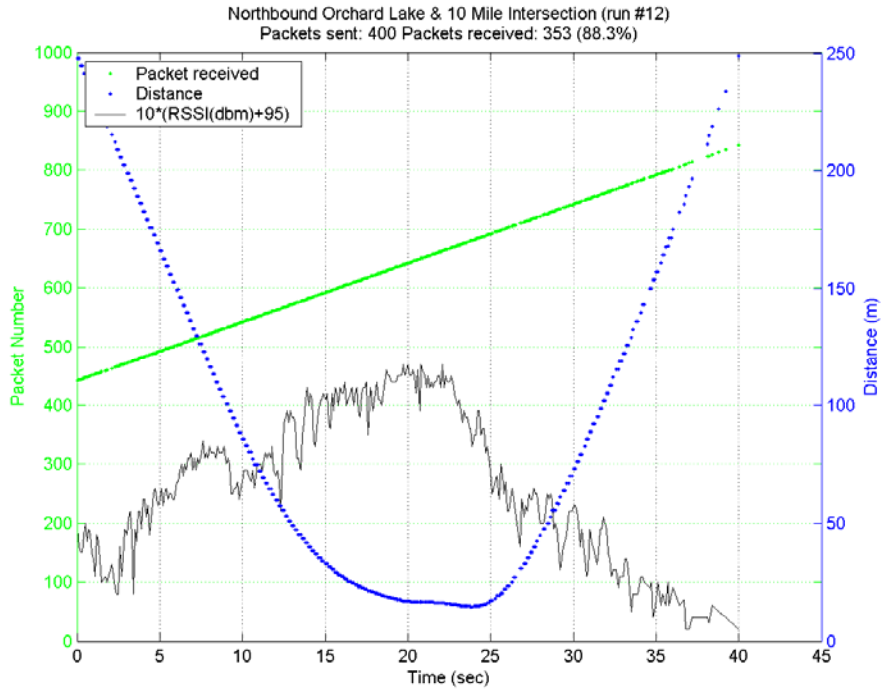



**Figure 70. Northbound 10 Mile Rd. Packets Received, Range, and RSSI Within 250 m Range of Interest for Safety Applications**

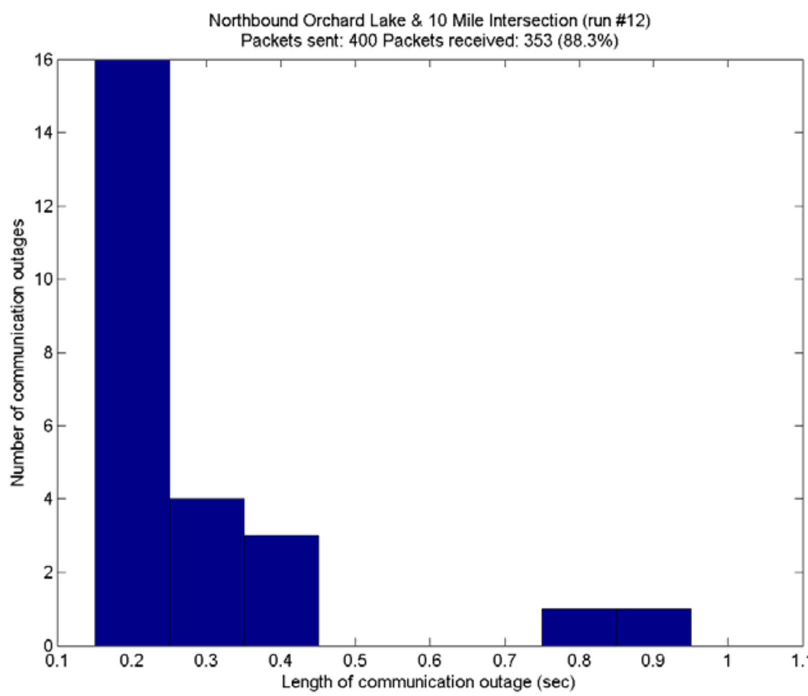



**Figure 71. Number of Outages and Length in Northbound Direction Within 250 m**

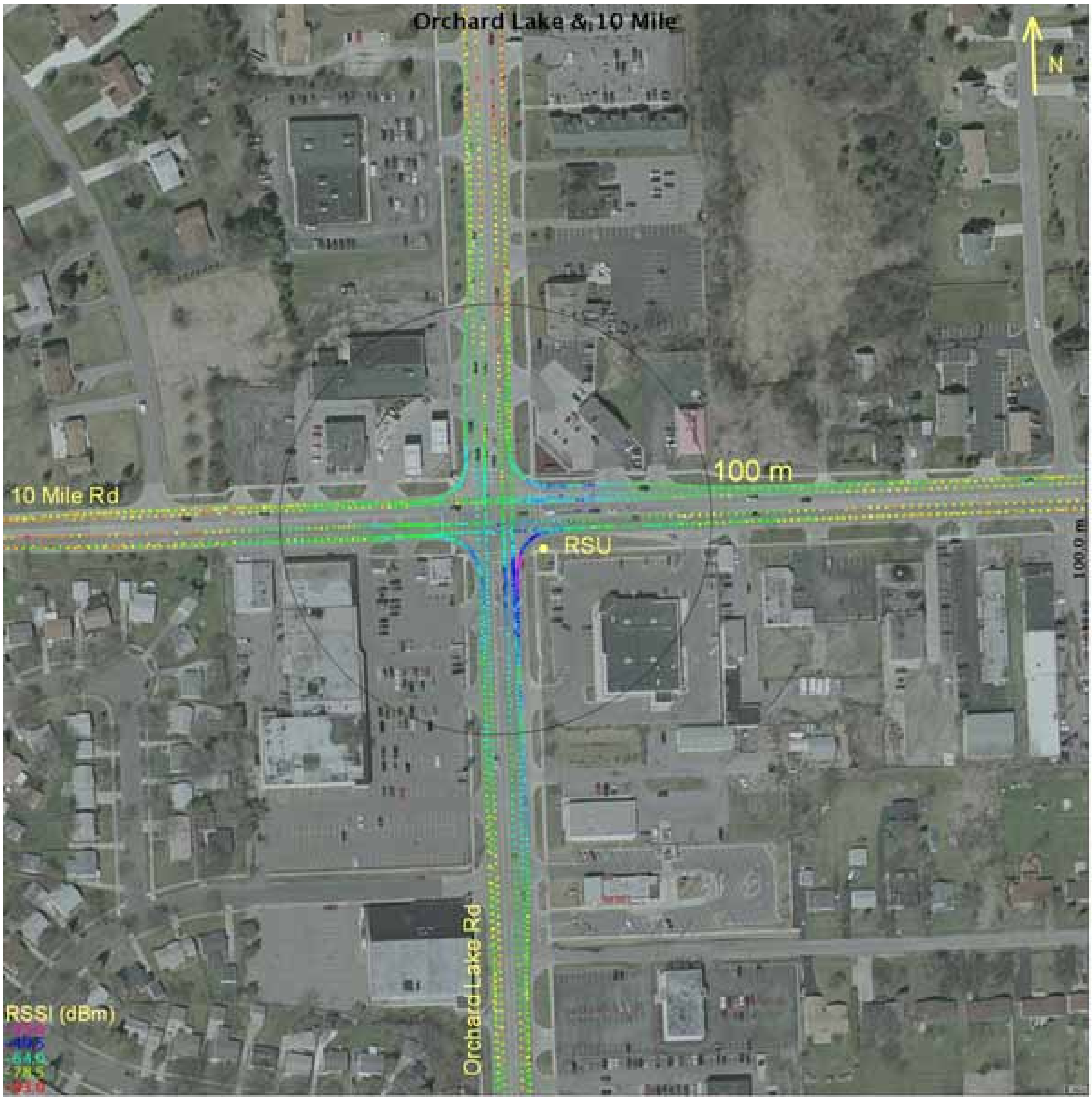



**Figure 72. RSSI Level and Packet Reception in All Directions and Multiple Lanes at Orchard Lake and 10 Mile Road Within 250 m of RSU Location**

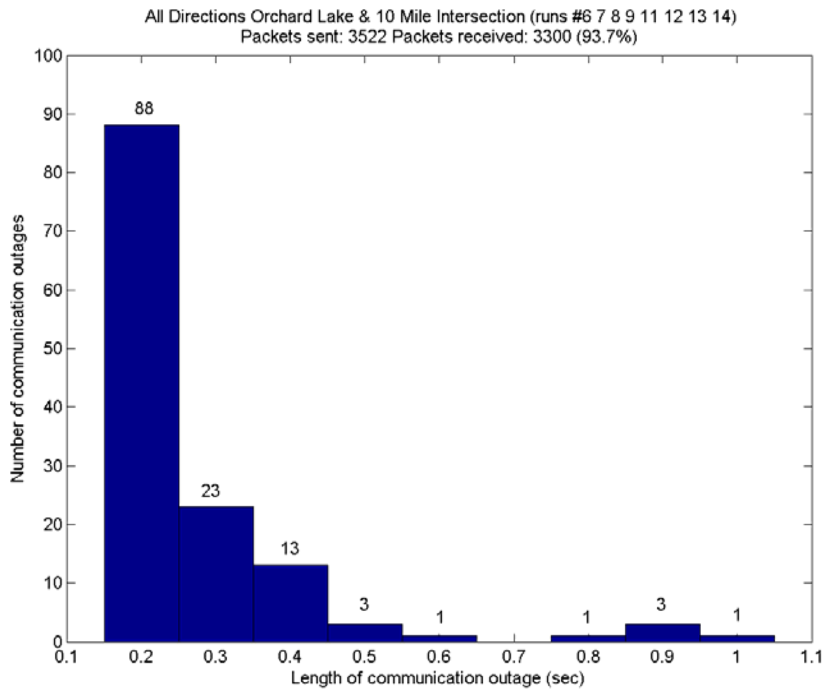



**Figure 73. Cumulative Number of Outages and Respective Length of Time at Orchard Lake and 10 Mile Road Within 250 m of RSU Location**

Figure 72 shows an overlay of colorized RSSI values on top of an aerial photograph of the intersection. As expected, the RSSI value was highest closer to the RSU and sporadic packet losses occurred at ranges closer to 250 m. The cumulative successful transmission ration was 93.7 percent. It is worth noting again that this was achieved under a sub-optimal RSU antenna setting (intersection corner, 10 ft above the ground) and with an inverted OBU roof-mount antenna, clearly not optimized for RSU conditions.

Figure 73 shows the cumulative number of outages from all the test runs along with their length in seconds. The most frequent outages (88) are of the minimal kind (i.e., 200 ms). This kind of outage is certainly the easiest outage to remedy with data coasting techniques. As mentioned earlier, the longer outages (around one second) are either due to hilly terrain or road sign obstructions and should be substantially reduced with proper RSU antenna placement.

In light of all the previous plots and results, it can be concluded that the RSU-OBU communication at this intersection was relatively high (above 93%) within the required range of 250 meters.

### *3.2.2 Traffic Signal Controller Phase and Timing*

The RSU message being sent by the RSU contained, as described in Table 9, information regarding the current signal status for each direction as well as the time remaining in the current state. This information was received by the OBU as it traveled through the intersection and would have been available, in real-time, to a safety application such as traffic signal violation warning if it were implemented on-board the vehicle. To illustrate the type of information in the RSU message that the OBU received during the multiple runs, Figure 74 shows the distance and velocity (*10) of the OBU color-coded with the received signal status. At about 325 m west of the RSU, the light turned yellow. The driver started slowing down when the light turned red at about 200 m (10-second tick mark on time line). The OBU came to a full stop before driving through the intersection when the light turned green (just beyond the 40-second tick mark on the time line). The collected data showed that the red phase lasted 34 seconds as expected for this leg of the intersection.

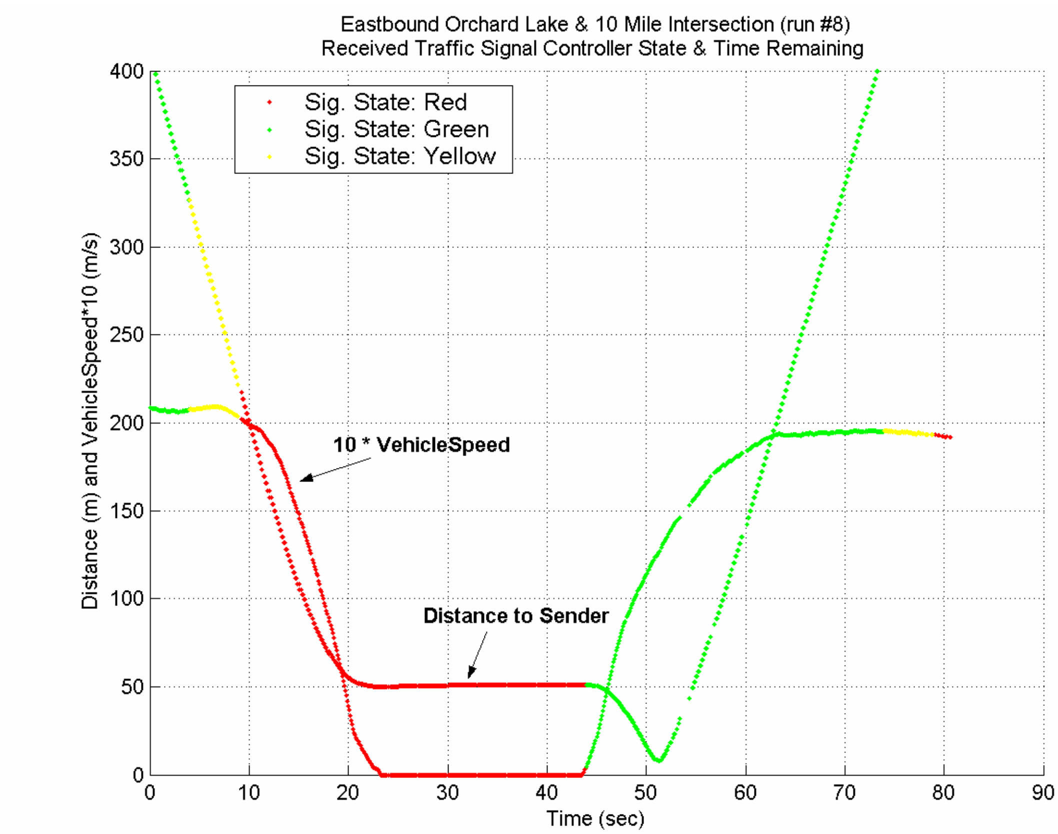



**Figure 74. Distance, Vehicle Speed, and Signal State for an Eastbound Run**

Figures 75 and 76 illustrate the signal state and time remaining in the eastbound direction as received by the OBU while traveling through the intersection. It is easy to notice that the resolution of the time to next state is one second, which is not adequate for anticipated safety applications. This is a limitation of the EPAC M30 serial interface. The other limitation is the inability to “poll” the data at a faster rate than 200 ms. In the case where one attempts to interface directly to the existing intersection controller with the objective of developing safety applications, special attention and effort will be required to deal with these interface issues.

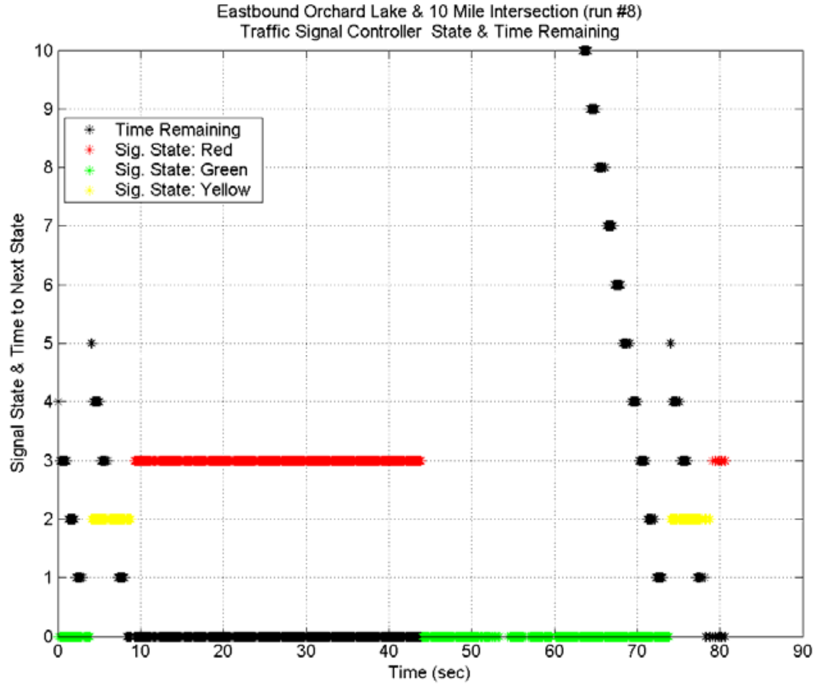



**Figure 75. Signal State and Time to Next State as Received by OBU**

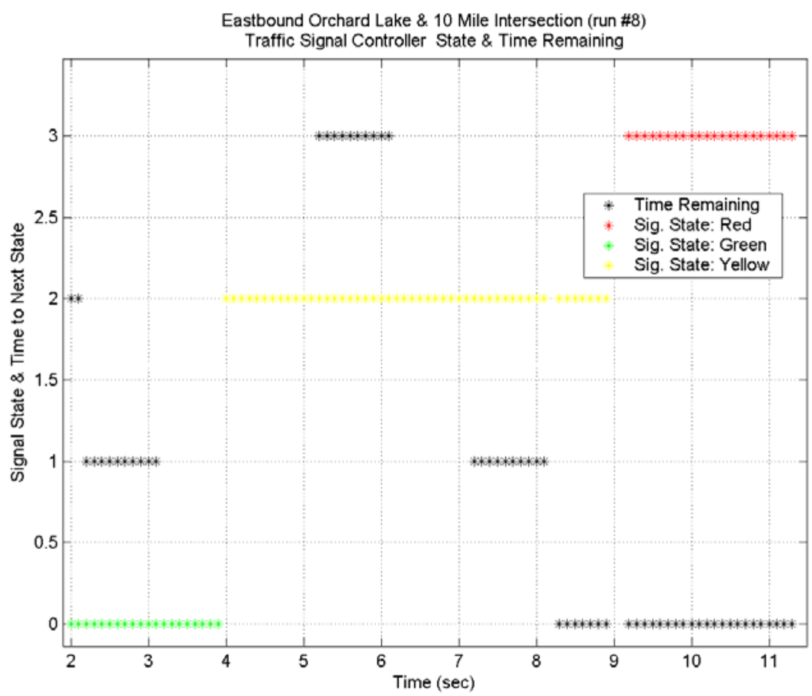



**Figure 76. One-Second Quantization of Time to Next State as Received by OBU**


**Figure 77. Orchard Lake & 10 Mile Rd intersection. Current Signal State as Received by the OBU From the RSU**

Finally, the signal state was overlaid on top of the aerial photograph of the intersection in Figure 77 to give the reader a better view of "what was received" and "when it was received" from the RSU as the OBU drives through the intersection.

## 3.3 Reduced Power Transmit Testing and 5.9 GHz DSRC Intersection Characterization

The next set of tests was performed at reduced transmission power levels of 12, 6 and 3 dBm. The tests were intended to explore the potential of limiting the maximum range of communication in a real-world intersection setting via power control.

### *3.3.1 Test Results at 12 dBm Transmit Power Setting*

The following table summarizes the configuration of the RSU-WRM.

| *Packet Length (bytes)* | *Message Interval (ms)* | *Data Rate (Mbps)* | *Transmit Power (dBm)* |
|---|---|---|---|
| *500* | *100* | *6* | *12 dBm* |

**Table 11. WRM configuration for RSU message (12dBm)**

Figure 78 summarizes the data collected at the 12 dBm power level setting for an eastbound run. Compared to the results under full power setting in Figure 60, the maximum range of communication dropped approximately from 500 m to 350 m.

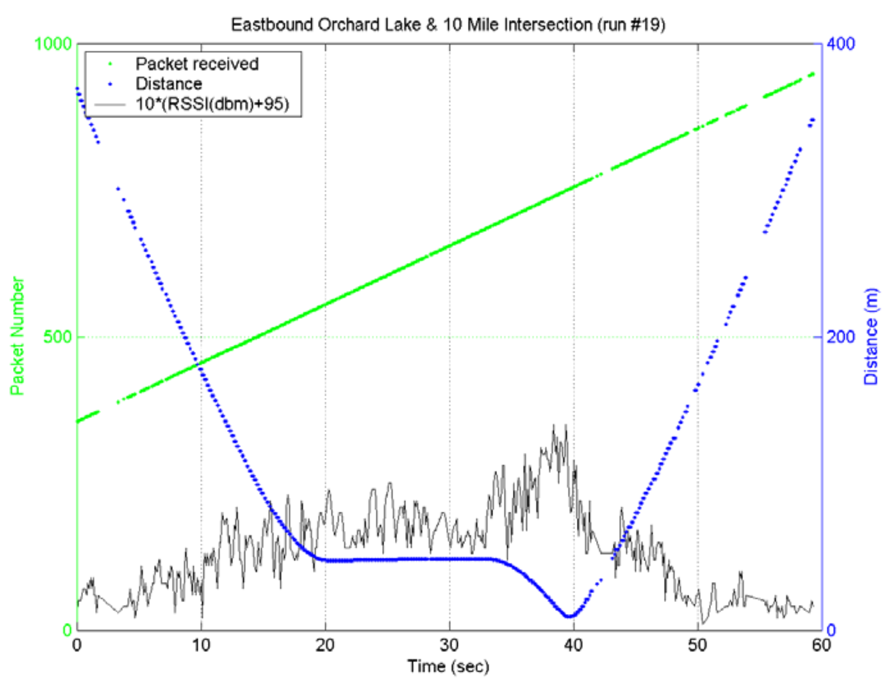



**Figure 78. Eastbound 10 Mile Rd. Packets Received, Range, and RSSI @ 12 dBm**

Figure 79 summarizes the data collected at the 12 dBm power level setting for a westbound run. Again, the maximum range of communication dropped from 550 m (full power setting), see Figure 61, to approximately 375 m. Note the sharp RSSI drop at 30 seconds in the time line as a truck blocked the direct line of sight between the OBU and the RSU for a full 30-second period. Both the truck and the OBU vehicle were stopped at a red light. No packets were lost during that obstruction.

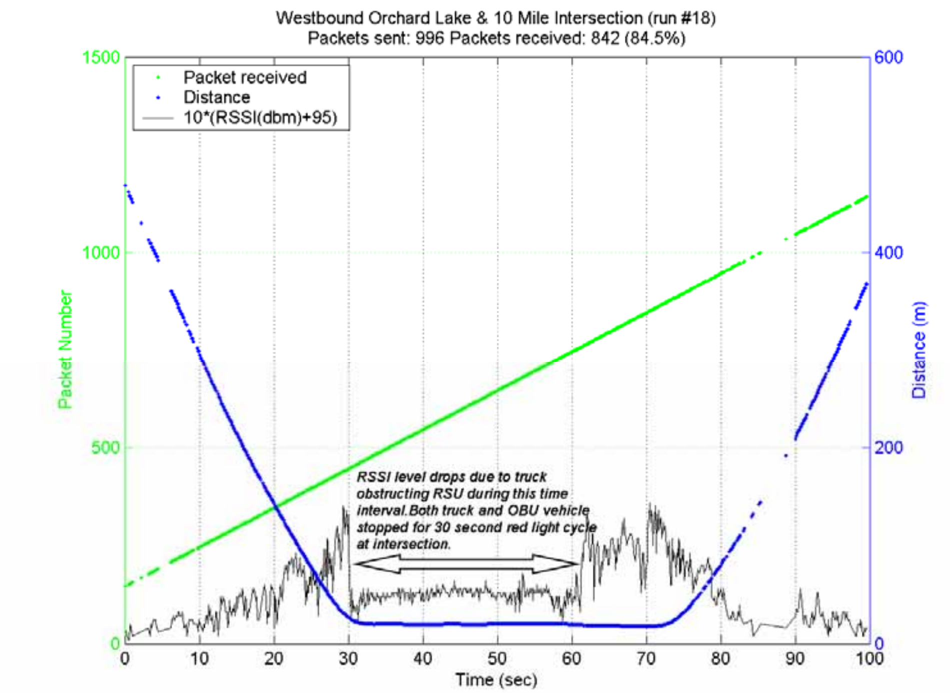



**Figure 79. Westbound 10 Mile Rd. Packets Received, Range, and RSSI @ 12 dBm**

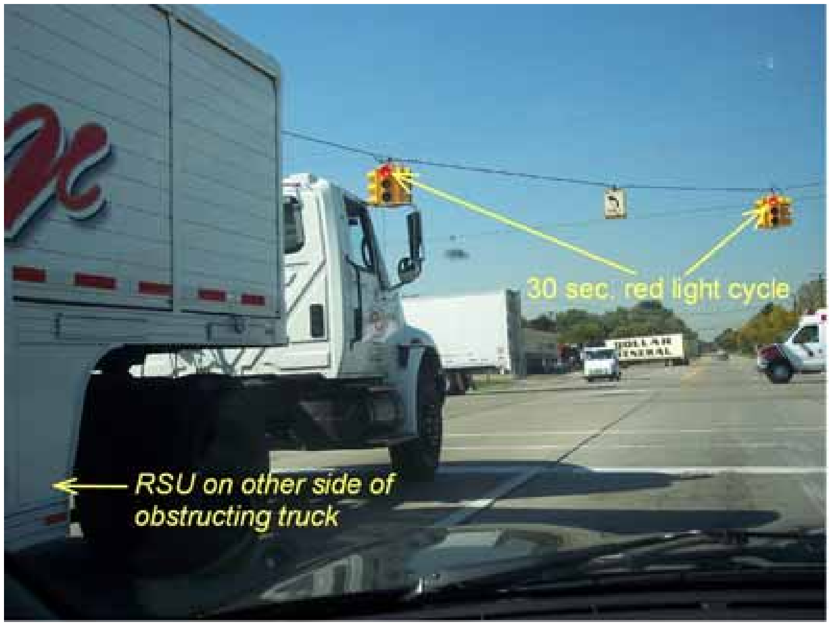



**Figure 80. RSU to the Left of Truck Being Obstructed From OBU**

### *3.3.2 Test Results at 6 dBm Transmit Power Setting*

The following table summarizes the configuration of the RSU-WRM.

| *Packet Length (bytes)* | *Message Interval (ms)* | *Data Rate (Mbps)* | *Transmit Power (dBm)* |
|---|---|---|---|
| *500* | *100* | *6* | *6 dBm* |

**Table 12. WRM Configuration for RSU Message (6 dBm)**

Figure 81 summarizes the data collected at the 6 dBm power level setting for a westbound run. Compared to the results under full power setting, the maximum range of communication dropped approximately from 550 m to 300 m with a substantial amount of lost packets above 150 m.

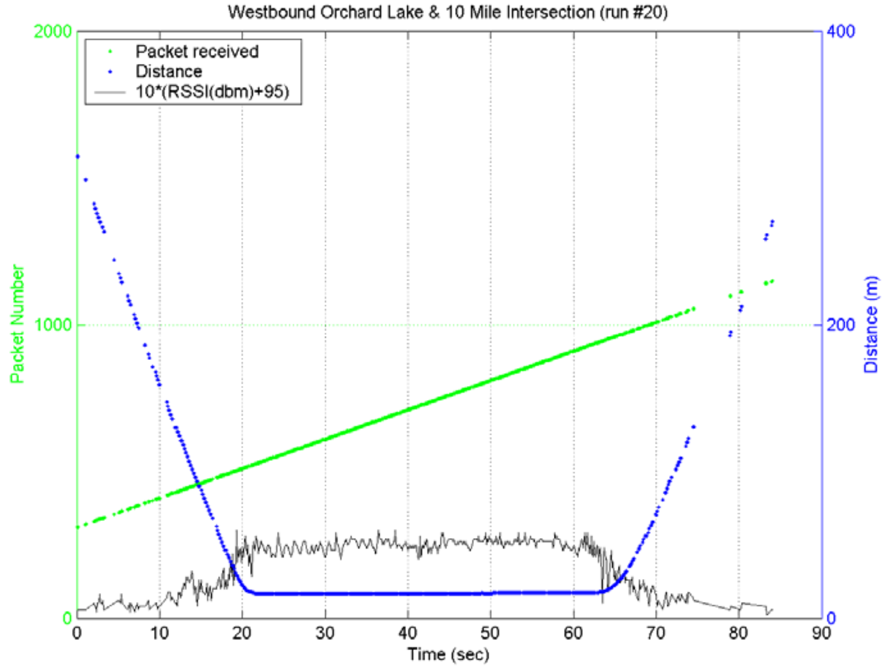



**Figure 81. Westbound 10 Mile Rd. Packets Received, Range, and RSSI @ 6 dBm**

Figure 82 shows the maximum range of communication around 150 m for the eastbound run.

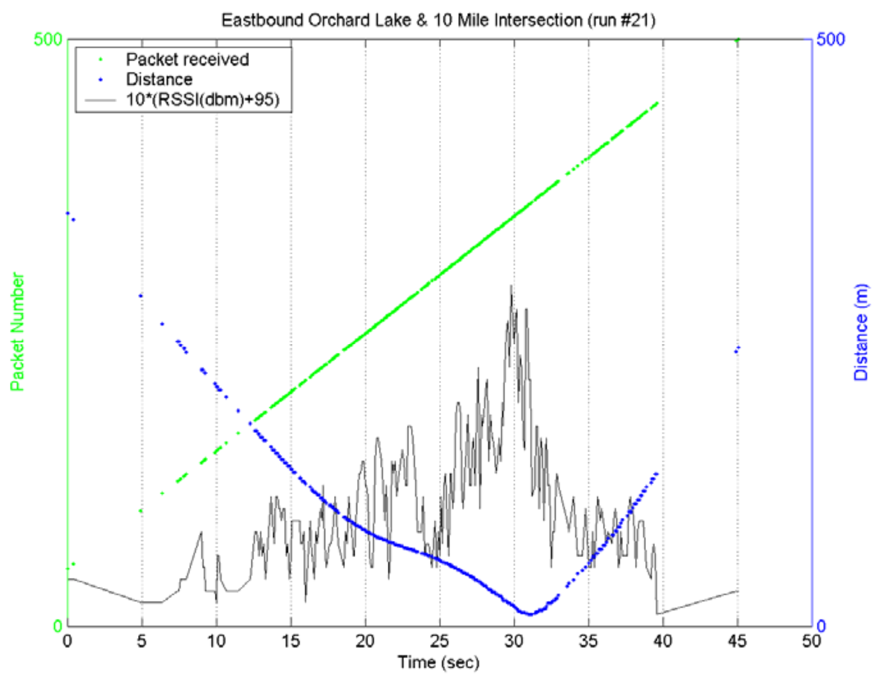



**Figure 82. Eastbound 10 Mile Rd. Packets Received, Range, and RSSI @ 6 dBm**

### *3.3.3 Test Results at 3 dBm Transmit Power Setting*

The following table summarizes the configuration of the RSU-WRM:

| Packet Length (bytes) | Message Interval (ms) | Data Rate (Mbps) | Transmit Power (dBm) |
|---|---|---|---|
| 500 | 100 | 6 | 3 dBm |

**Table 13. WRM Configuration for RSU Message (3 dBm)**

Figures 83 and 84 show a similar maximum range of communication for both the 3 dBm and the 6 dBm power settings.

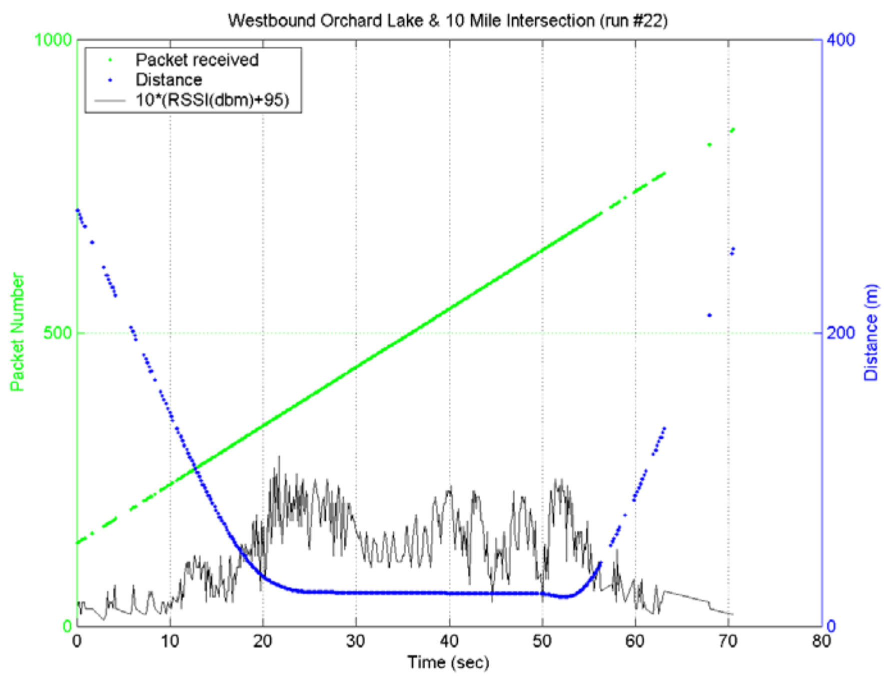



**Figure 83. Westbound 10 Mile Rd. Packets Received, Range, and RSSI @ 3dBm**

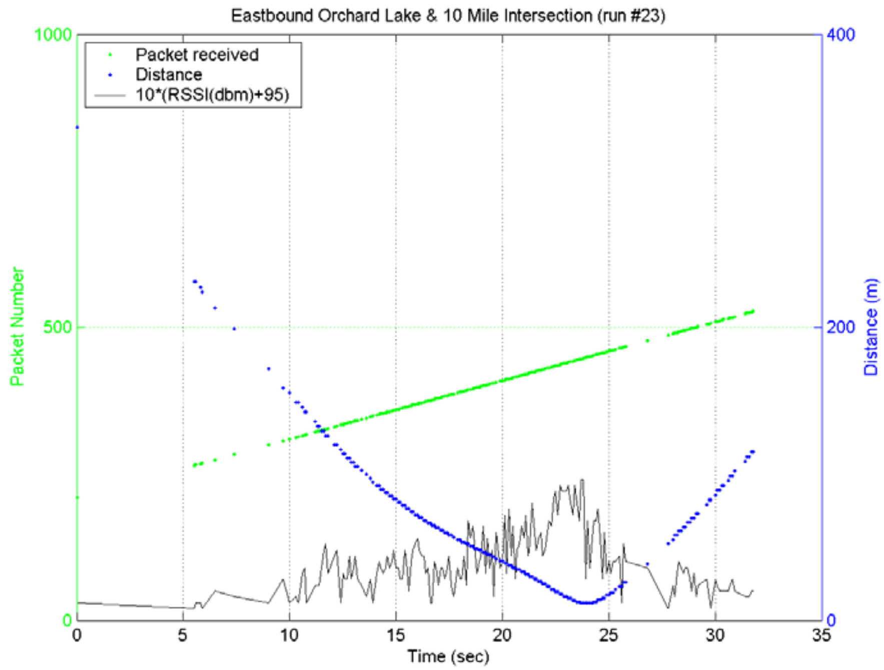



**Figure 84. Eastbound 10 Mile Rd. Packets Received, Range, and RSSI @ 3 dBm**

Figure 85 conveys the notion that some form of range control can be achieved at a real intersection with the proper selection of transmission power. The points on the graph are composites drawn from all of the data sets.

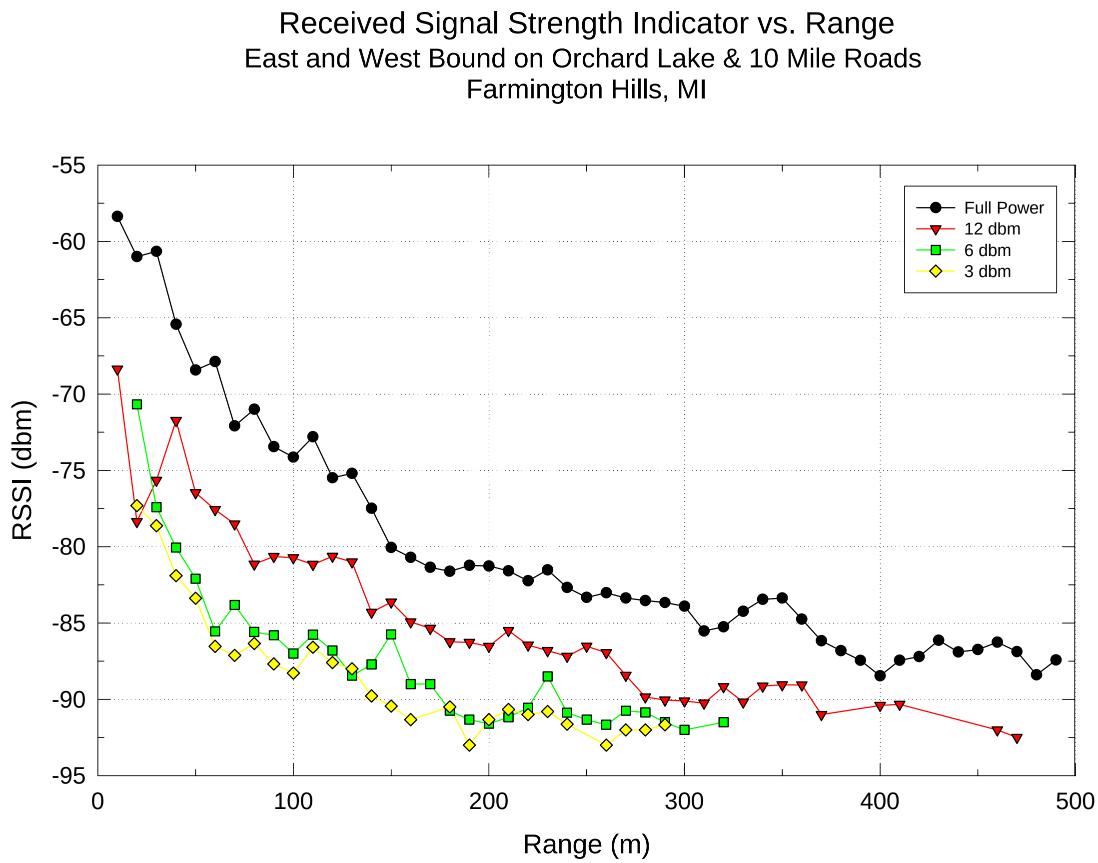



**Figure 85. RSSI versus Range at Various Power Settings**

## 3.4 Vehicle-Vehicle and Vehicle-Infrastructure Testing and Results

The final set of tests was aimed at collecting data to analyze whether communications between two OBU vehicles, traveling on perpendicular legs of the intersection, can be established before one of the OBUs enters the intersection. If so, how far away from the intersection RSU is that v2v communication initiated? It is generally assumed that in an urban intersection with high building densities, this type of v2v communication would not be possible. But since this intersection had a relatively low building density it was decided to explore this type of scenario. The transmission power on all WRMS was reconfigured to full setting (~20 dBm).

The results are illustrated in Figure 86. In this scenario a GM-OBU vehicle traveled eastbound while a Ford-OBU traveled southbound towards the RSU. The RSU was transmitting its RSU message while receiving both OBUs common vehicle message set. Both OBUs interfaced with their respective vehicle CAN buses to send out actual vehicle sensor messages such as speed, accelerations, and yaw rate.

The tracks on the figure below in the eastbound direction depict the range of the GM-OBU to the Ford-OBU as a calculated value after a successful reception of each other's messages. The range is colorized so that it is easy to determine where the vehicles were relative to each other when they successfully exchanged messages.

For example, the GM vehicle started receiving the Ford-OBU message about 100 m from the intersection (purple/blue dots), while the Ford-OBU received the GM-OBU message at about 200 m from the intersection (matching blue/purple dots). It is worth noting that because of the building on the northwest corner of the intersection no visual line of sight was available to the drivers as they approached the intersection. Examining Figure 87, where the scenario consisted of the Ford-OBU traveling northbound while the GM-OBU was traveling westbound, similar observations can be made.

Figure 88 shows that in this case, the v2v communication was established when the Ford vehicle was at ~70 m from the RSU while the GM vehicle was at ~160 m east of the RSU. Again in this case, the v2v communication was established before the actual visual line of sight between the drivers because of a building on the southeast corner of the intersection.

The data also showed that RSU message reception by both vehicles could be qualified as typical in the sense defined earlier at full power settings (beyond 500 m and above 90% within 250 m of the RSU).

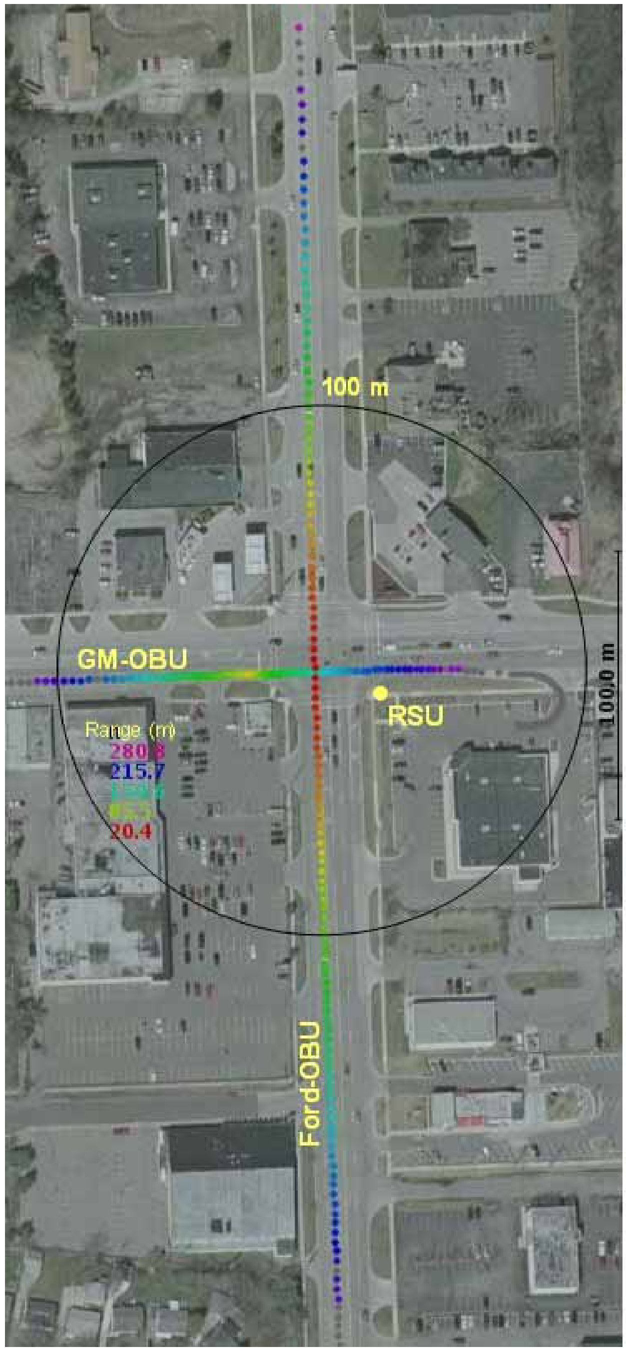



**Figure 86. One RSU and Two OBUs Crossing Paths Testing. GM-OBU Traveling Eastbound, Ford-OBU Traveling Southbound.**

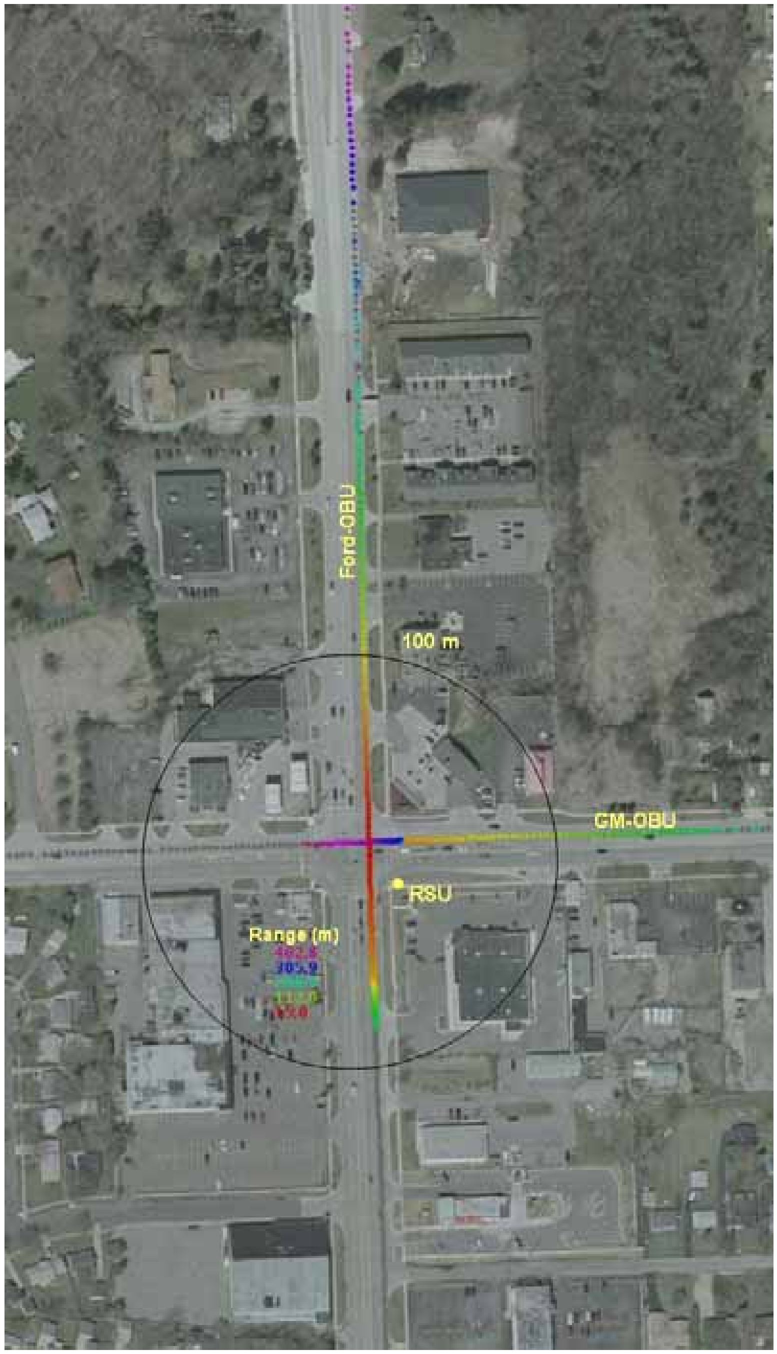



**Figure 87. One RSU and Two OBUs Crossing Paths Testing. GM-OBU Traveling Westbound, Ford-OBU Traveling Northbound.**

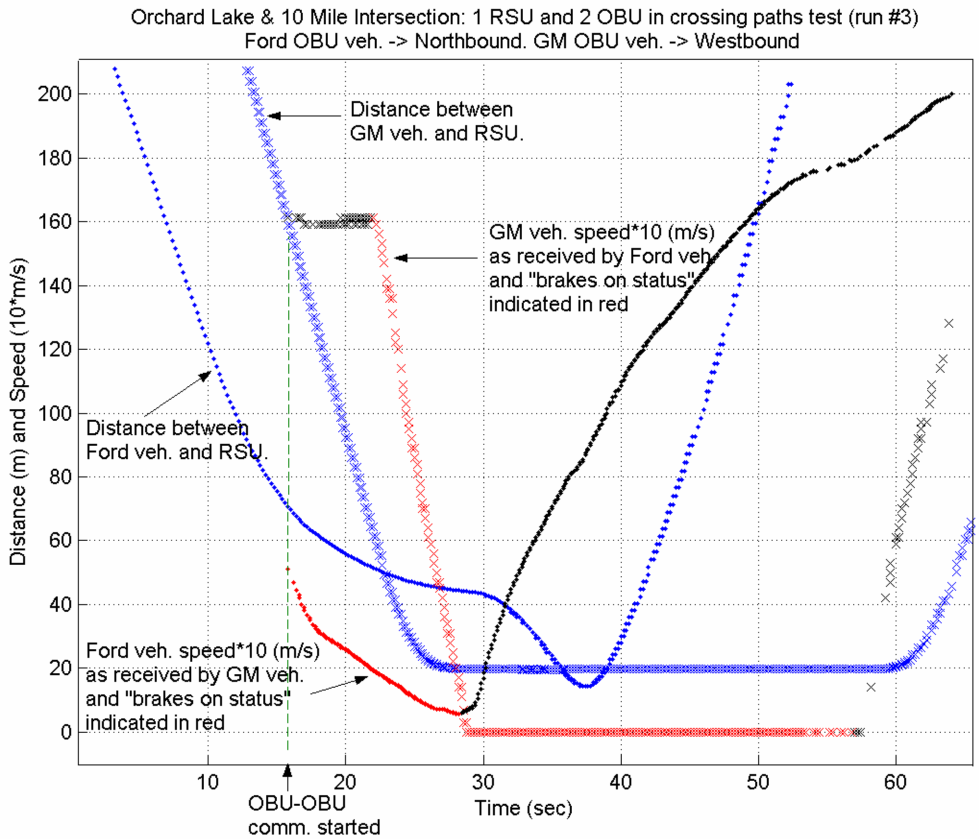



**Figure 88. Range from RSU, Vehicle Speed and Braking Information as Received by GM-OBU and Ford-OBU While Traveling on Intersection Crossing Paths**

## 3.5 Summary

In light of the testing performed at Orchard Lake and 10 Mile Road, the following conclusions can be drawn:

- The EPAC M30 traffic signal controller was successfully synchronized with the installed controller at the intersection.

- Even though the traffic controller (signal state & time remaining) was properly received by the OBU, the resolution of the time remaining (1 second) was not adequate. Interfacing to a traffic controller proved to be more challenging than expected and the final output was not adequate for anticipated safety applications. In the case of a fixed timing cycle, where there is no adaptation based on sensor feedback of vehicles in the intersection, a more precise timing could be generated, on the OBU side as part of the safety application, by initializing a timer as soon as a transition between signal states is received as part of the RSU message. However, to satisfy the 100 millisecond safety applications update rate requirement for the RSU message (instead of the 200 millisecond achieved with the EPAC M30), the signal controller software and serial protocol would require more elaborate modifications.

- Wireless communication at 5.9 GHz at this intersection was overall characterized with a ~93% successful transmission ratio over the range of interest of 250 m.

- This performance was achieved under a sub-optimal RSU antenna setting (intersection corner, 10 ft above the ground) and with an inverted OBU roof-mount antenna, clearly not optimized for RSU conditions.

- For a safety application such as traffic signal violation warning, no major issues were uncovered as far as fulfilling the basic requirements from Task 3. No GPS outages were noticed since there are no overhead obstructions.

- Most of the outages were of the "minimal" kind, i.e. one packet loss at a time, which should be a containable type of outage.

- Some of the longer outages were merely due to obstruction (road signs, hill) and should be minimized with better (optimal) RSU antenna placement.

- Some level of maximum transmission range control can be achieved at a real-world intersection with the proper selection of transmission power.

- Finally, the limited set of tests performed for this RSU and two OBUS on crossing paths scenario and the results derived from it shows that in this intersection, communication between the two OBUs was achieved, even before visual line of sight between the drivers. It suggests that perhaps the idea of having to relay OBU messages by RSU may not necessarily be needed at some intersections. Further studies and tests are needed for this specific scenario.

# 4 VEHICLE-TO-VEHICLE COMMUNICATIONS RESULTS USING THE WAVE RADIO MODULES

Task 6D of the VSC project developed the WAVE Radio Modules (WRMs) that were largely compliant with the ASTM 5.9 GHz DSRC/WAVE lower layer standards specifications. Task 9 of the VSC project developed the software application that allows the user to send and receive messages using the WRMs. This application runs on a Windows Laptop and communicates with the WRM via an ethernet interface. The application has a serial interface to the DGPS Max receiver, a CAN interface to vehicle sensor data, and a serial interface to the traffic signal controller. The WRMs and the Task 9 application were developed under a subcontract with DENSO LA Labs.

Several tests were conducted to evaluate the performance of the WRMs under vehicle-to-vehicle communications scenarios. This section describes the results of the vehicle-to-vehicle communications testing conducted at the Milford Proving grounds, I-96 freeway, and the M-5 ramp to Twelve Mile Road in Michigan.

## 4.1 Vehicle-to-Vehicle Communications Performance at Milford Proving Grounds

The vehicle-to-vehicle communications testing was conducted using a Jaguar XKR developed by Ford for the EDMap project, and a Buick Lesabre developed by GM for the ACAS project. Software modifications were carried out on both these vehicles so that they provide the vehicle signals over the CAN interface as defined in the Task 9 application. The vehicle position information was obtained from the DGPS Max receiver that was configured to obtain differential corrections from the U.S. Coast Guard beacons. One roof mount DSRC antenna (developed under the VSC Task 6C project) was used on each of the vehicles.

The legend for the vehicles used in the testing is shown in Figure 89. An illustration of the test track used at the Milford Proving Grounds (MPG) for the testing is shown in Figure 90. In all tests the WRMs were configured to send and receive on the DSRC Control Channel, which is Channel 178 with a center frequency of 5890 MHz and a 10 MHz bandwidth.

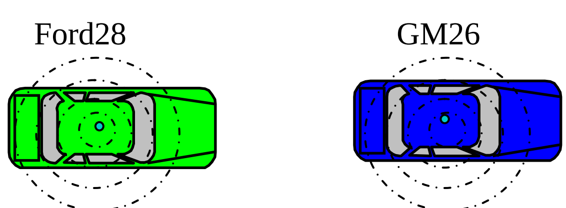



**Figure 89. Legend for Vehicles**

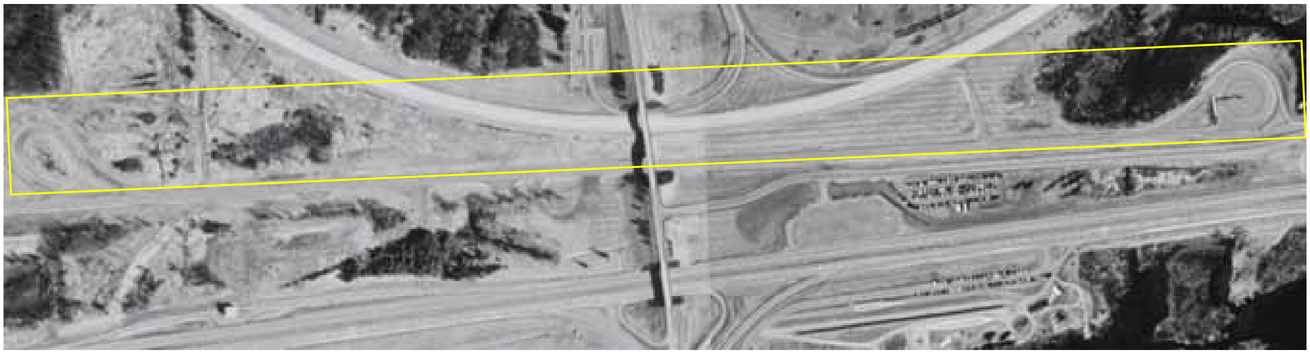


**Figure 90. Test Track at MPG**

### *4.1.1 Test for Omni-directional Coverage & Vehicle Signals*

This test scenario is shown in Figure 91. The parameters for this test are shown in Table 14.

| *Packet Length (bytes)* | *Message Interval (ms)* | *Data Rate (Mbps)* | *Transmit Power (dBm)* | *Desired Vehicle Speed (mph)* |
|---|---|---|---|---|
| *200* | *100* | *6* | *Full (~20 dBm)* | *20* |

**Table 14. Parameters for Test Scenario No. 4.1.1**

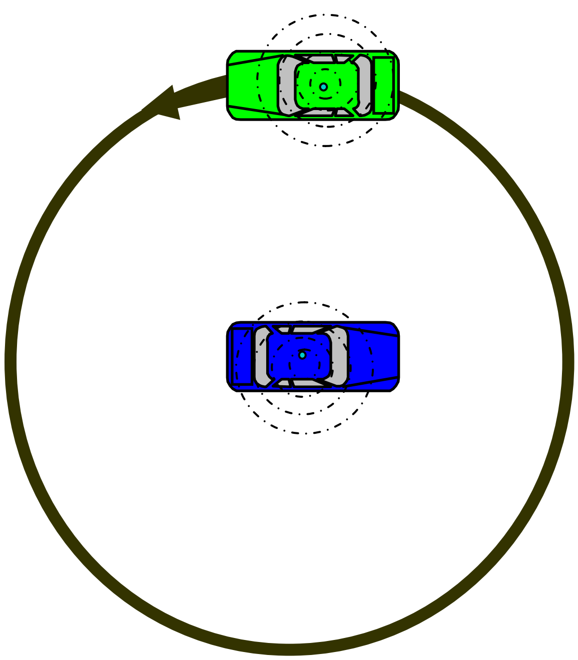


**Figure 91. Test Scenario No. 4.1.1**

In this test scenario, GM26 is stationary while Ford28 moves in the counter clockwise direction in a constant circular track around GM26. The WRMs on both vehicles were configured to both send and receive data. The results of this test scenario are shown in Figures 92 through 97. The distance between the vehicles was calculated from GPS data received by GM26. The distances are color-coded based on the received signal strength indicator (RSSI) values for the packets received by GM26.

Since both vehicles have been developed to provide vehicle signal data over the CAN interface to the Task 9 application, the communicated packets include actual vehicle signal data. Figure 93 shows the speed of Ford28, color-coded based on the brake status of Ford28, based on data received by GM26. Figure 94, Figure 95, and Figure 96 show the yaw-rate, longitudinal acceleration and lateral acceleration respectively of Ford28 based on data received by GM26.

The data from Figure 97 taken from a 90 second run showed that the number of packets from Ford28 received by GM26 is equal the number of packets sent by Ford28. Thus, this test scenario showed 100 percent reception and no packet loss. This demonstrated true omni-directional characteristics of the 5.9 GHz DSRC roof-mount antenna developed under Task 6 of the VSC project.

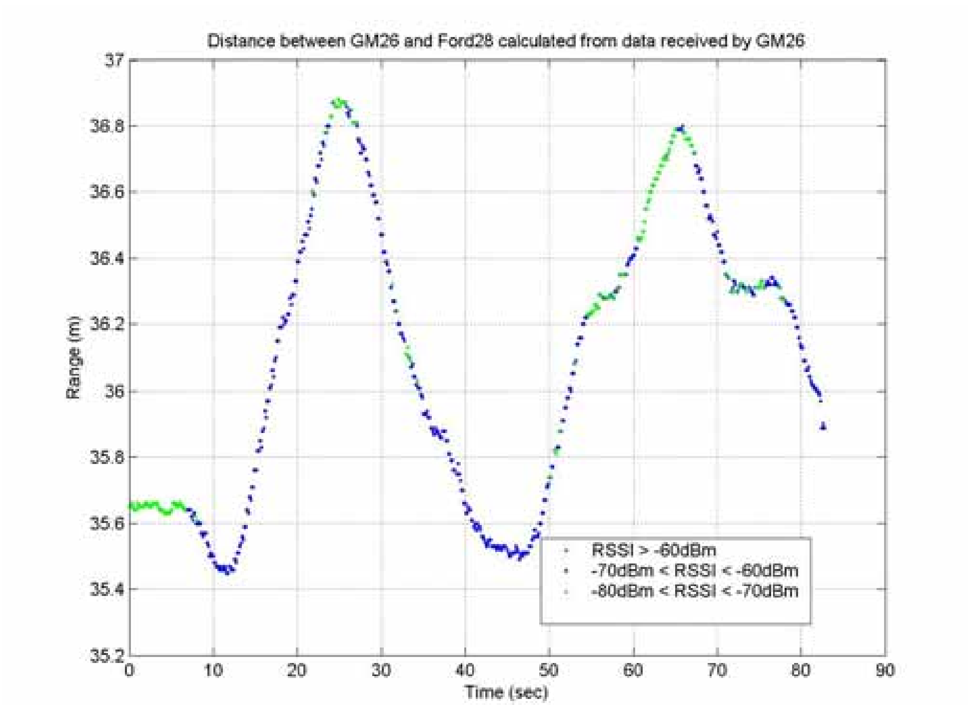



**Figure 92. Distance and RSSI Calculated from Data Received by GM26**

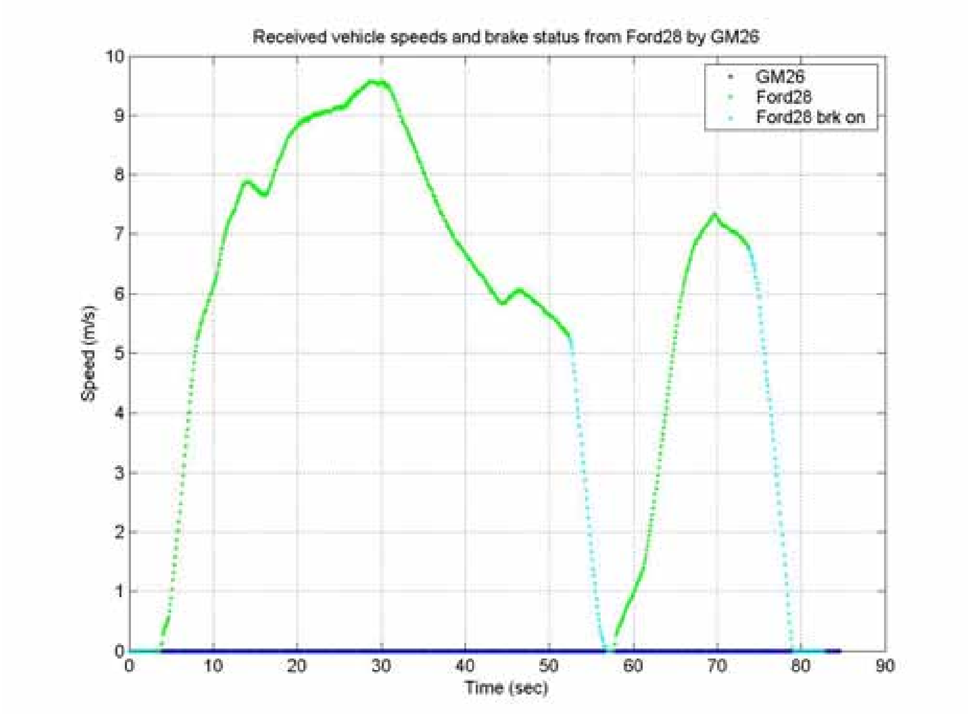



**Figure 93. Speed and Brake Status of Ford28 Received by GM26**

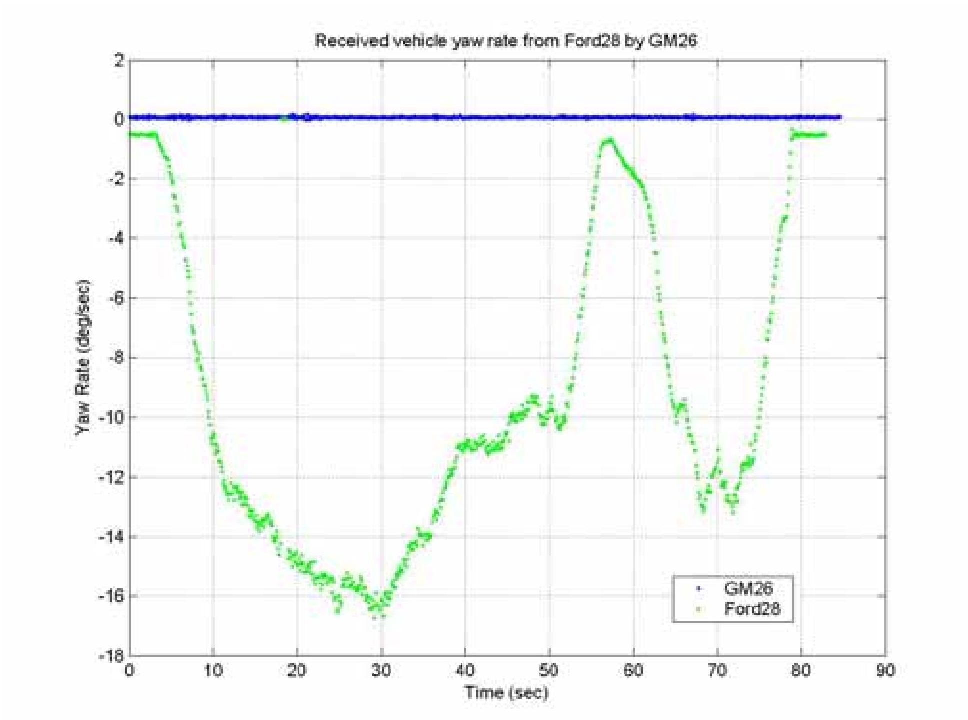



**Figure 94. Yaw Rate of Ford28 Received by GM26**

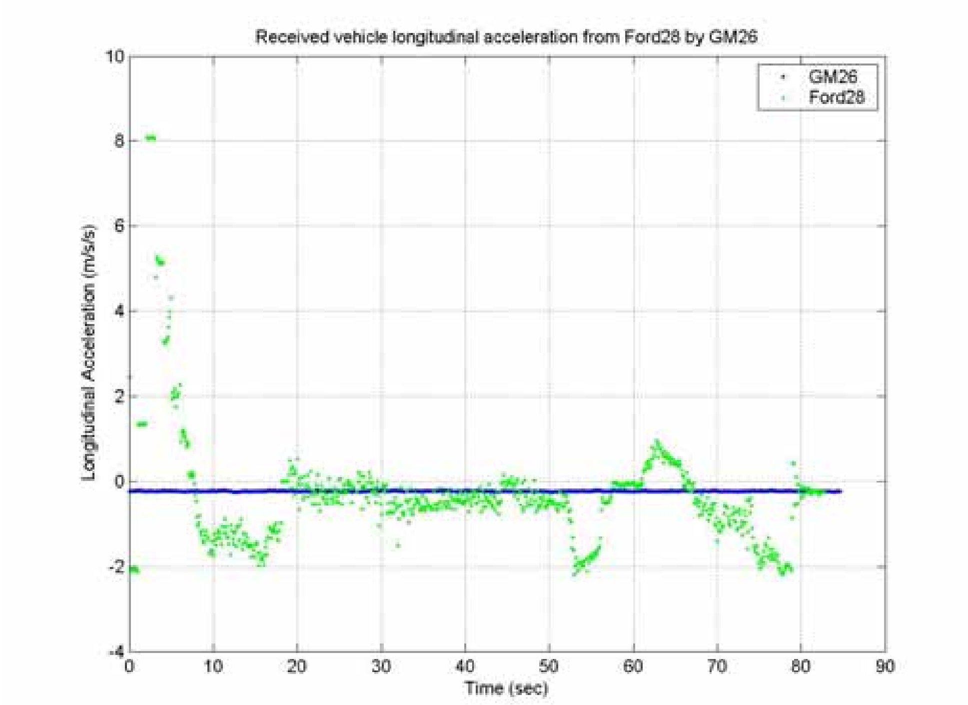



**Figure 95. Longitudinal Acceleration of Ford28 Received by GM26**

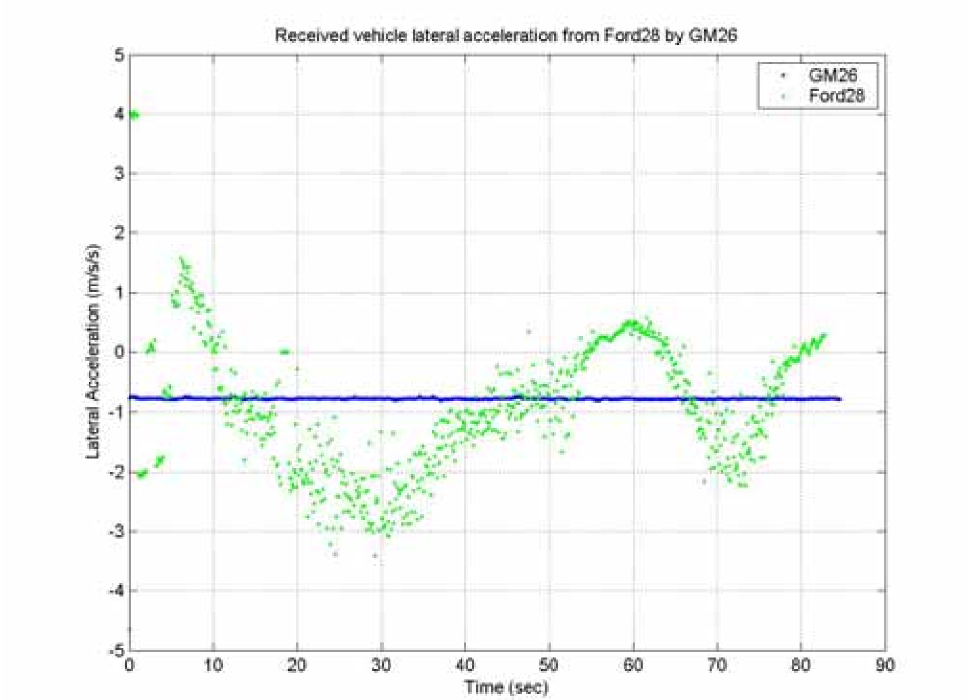



**Figure 96. Lateral Acceleration of Ford28 Received by GM26**

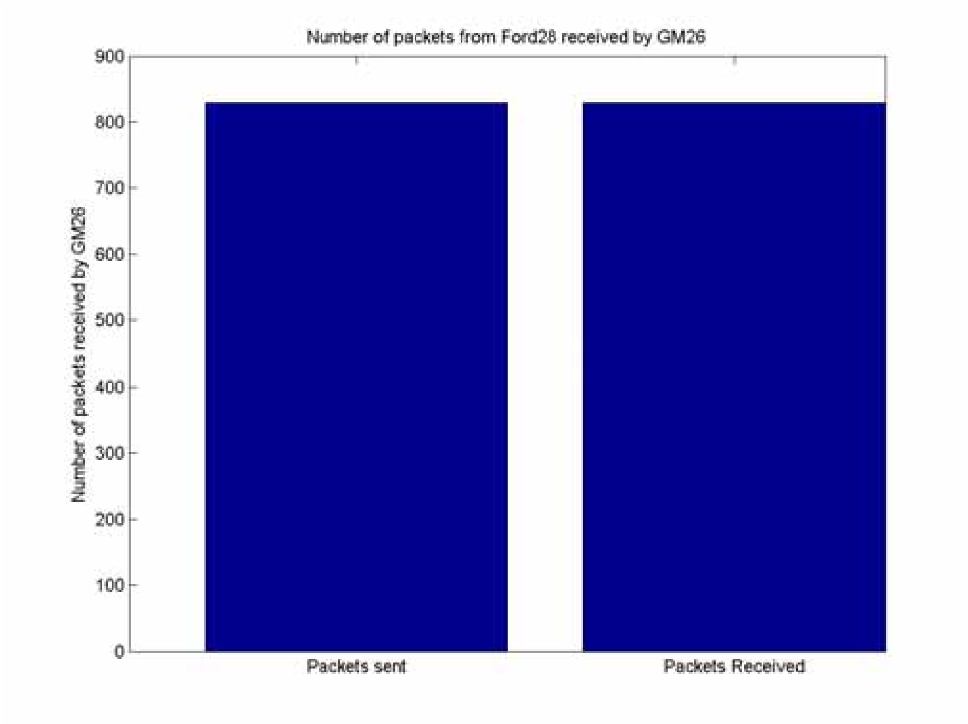



**Figure 97. Number of Packets from Ford28 Received by GM26**

### *4.1.2 Lead Vehicle Brake Test*

This test scenario is shown in Figure 98. The parameters for this test are shown in Table 15.

| *Packet Length (bytes)* | *Message Interval (ms)* | *Data Rate (Mbps)* | *Transmit Power (dBm)* | *Desired Vehicle Speed (mph)* |
|---|---|---|---|---|
| *200* | *100* | *6* | *Full (~20 dBm)* | *45* |

**Table 15. Parameters for Test Scenario No. 4.1.2**

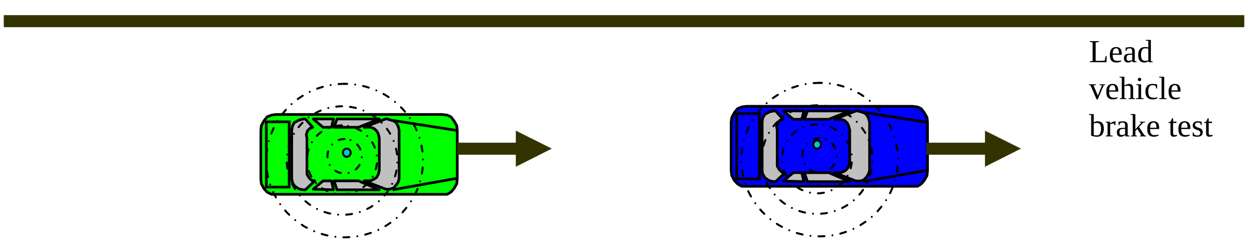



**Figure 98. Test Scenario No. 4.1.2**

In this test scenario, GM26 is the lead vehicle while Ford28 follows in the same longitudinal direction at about 45 mph. The lead vehicle brakes first and the following vehicle brakes in response to this. The WRMs on both vehicles were configured to both send and receive data. The results of this test scenario are shown in Figure 99 through Figure 102. The distance between the vehicles was calculated from GPS data received by Ford28. The distances are color-coded based on the received signal strength indicator (RSSI) values for the packets received by Ford28. Figures 100 and 101 show the speed and longitudinal acceleration based on data received by Ford28.

The data from Figure 102 taken from a 120 second run shows that the number of packets from GM26 received by Ford28 is equal the number of packets sent by GM26. This test scenario results showed 100 percent reception and no packet loss between the two vehicles up to ranges that exceeded 200 m. Thus, vehicle-to-vehicle communication using 5.9 GHz DSRC may potentially be used to prevent rear-end collisions between vehicles.

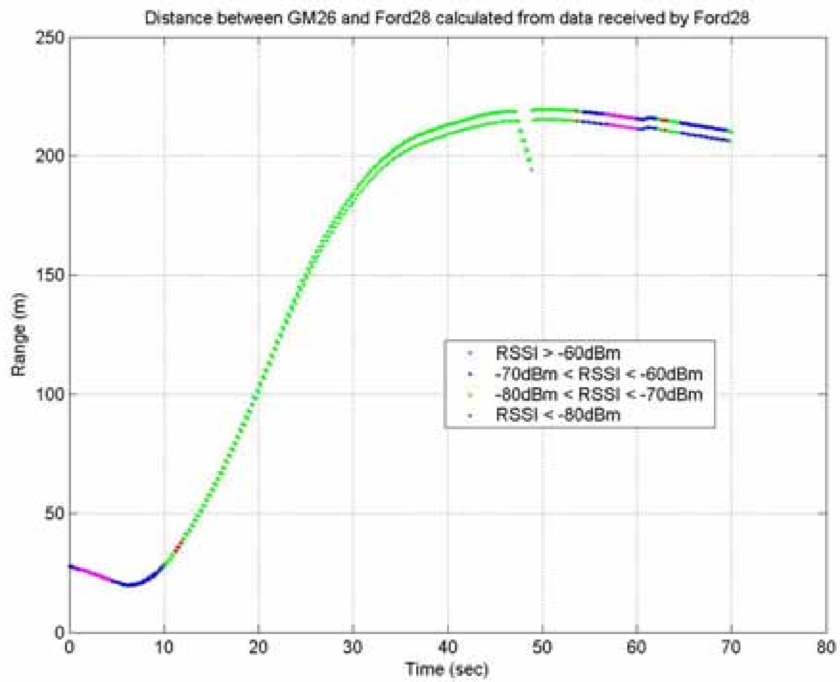



**Figure 99. Distance and RSSI Calculated from Data Received by Ford28**

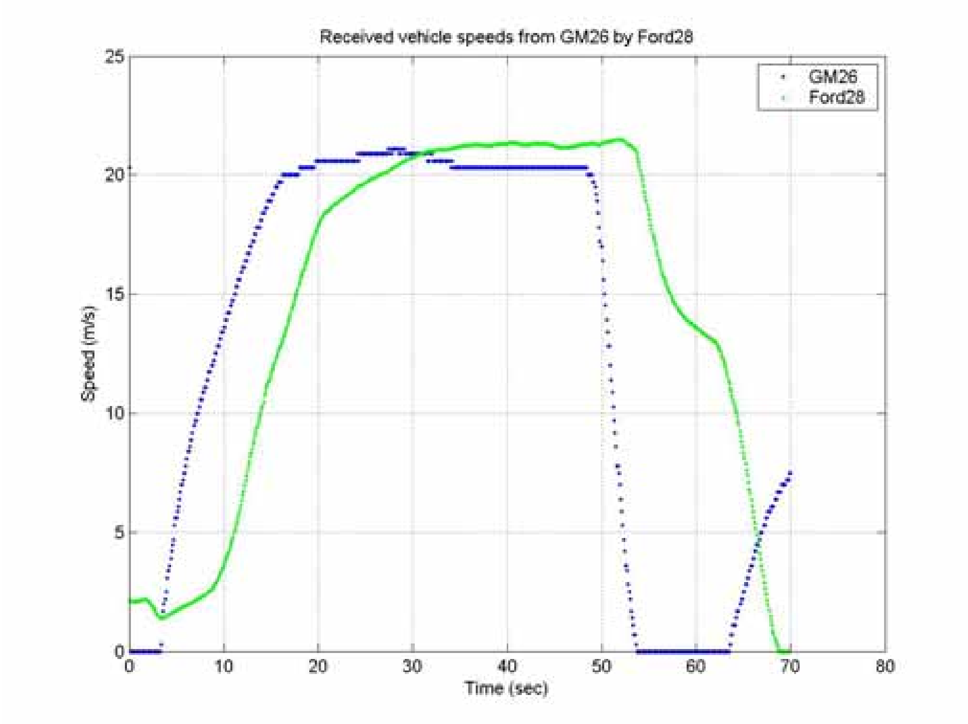



**Figure 100. Speed from Data Received by Ford28**

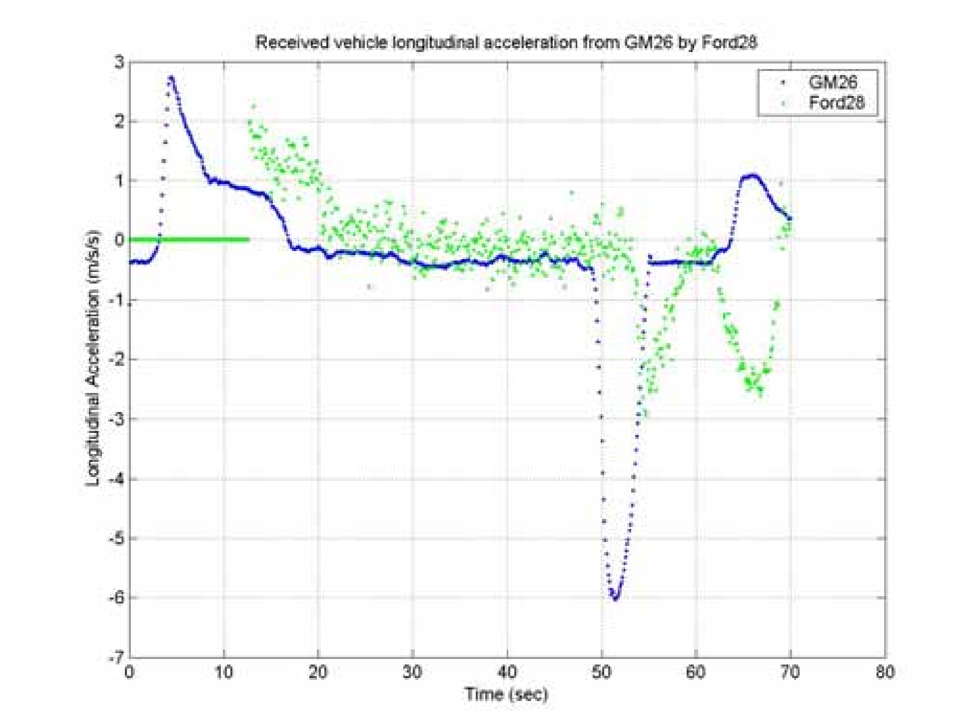



**Figure 101. Longitudinal Acceleration from Data Received by Ford28**

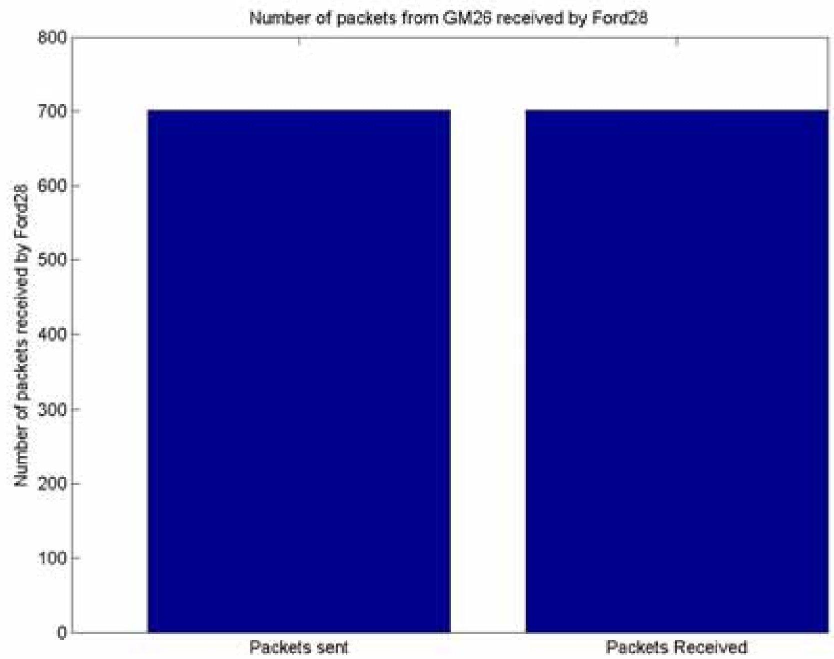



**Figure 102. Number of Packets from GM26 Received by Ford28**

### *4.1.3 Test for Maximum Communication Range*

This test scenario is shown in Figure 103. The parameters for this test are shown in Table 16.

| *Packet Length (bytes)* | *Message Interval (ms)* | *Data Rate (Mbps)* | *Transmit Power (dBm)* | *Desired Vehicle Speed (mph)* |
|---|---|---|---|---|
| *200* | *50* | *6* | *Full (~20 dBm)* | *10* |

**Table 16. Parameters for Test Scenario No. 4.1.3**

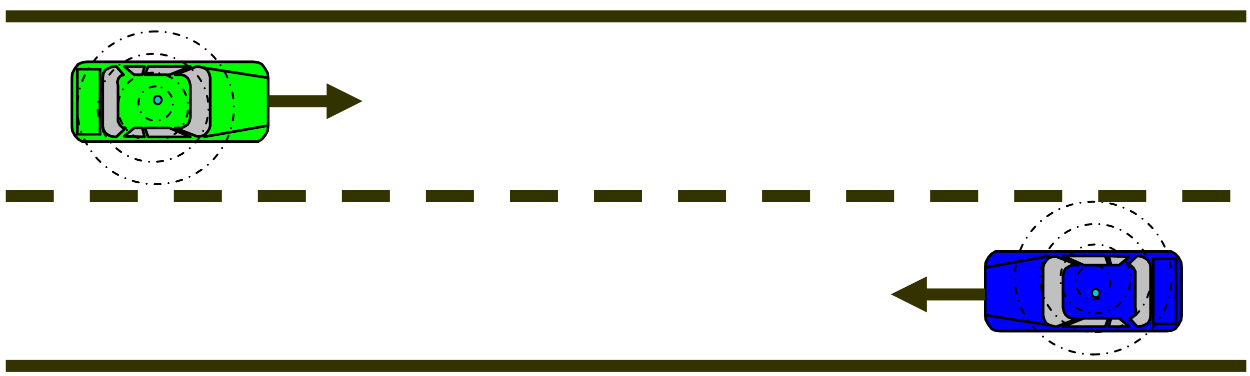


**Figure 103. Test Scenario No. 4.1.3**

In this test scenario, GM26 and Ford28 travel in opposite directions at about 10 mph thus yielding a relative speed of about 20 mph. This test was used to determine the maximum communication ranges and to determine if there are null zones for vehicle-to-vehicle. The WRMs on both vehicles were configured to both send and receive data. The results of this test scenario are shown in Figures 104 and 105. The distance between the vehicles was calculated from GPS data received by Ford28. The distances are color-coded based on the received signal strength indicator (RSSI) values for the packets received by Ford28.

The data from Figure 105 taken over a 100 second run showed that the number of packets from GM26 not received by Ford28 is less than 3 percent and most of the lost packets occur at distances greater than 550 m. The results of this test showed that vehicle-to-vehicle communication between the two vehicles is possible up to ranges that exceed 600 m on both directions of travel.

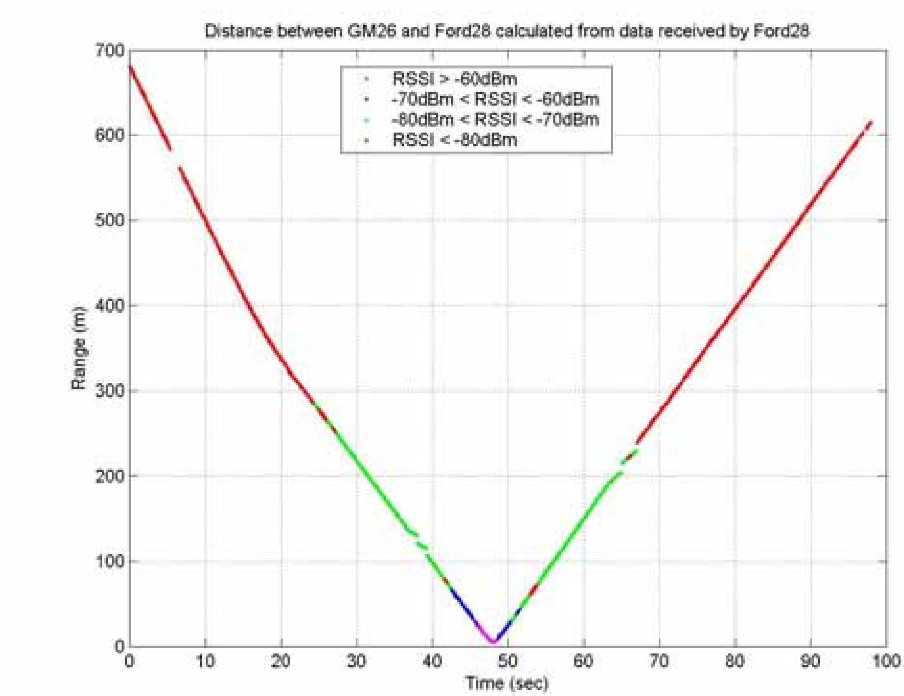



**Figure 104. Distance and RSSI Calculated from Data Received by Ford28**

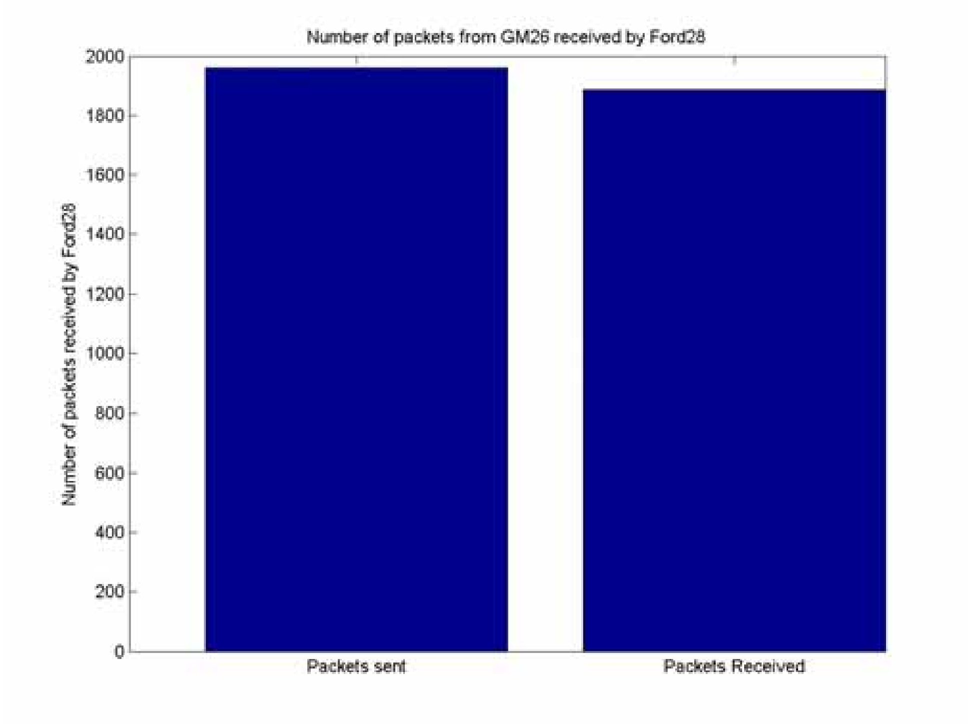



**Figure 105. Number of Packets from GM26 Received by Ford28**

### *4.1.4 Test for Communication Performance Under High Relative Speed*

This test scenario is the same as shown in Figure 103. The vehicle speeds for this test have been modified to 70 mph thus yielding a relative speed of 140 mph. The other parameters for this test are shown in Table 16.

This test was used to determine if there is degradation in communication performance under high relative speed conditions for vehicle-to-vehicle. The WRMs on both vehicles were configured to both send and receive data. The results of this test scenario are shown in Figures 106 and 107. The distance between the vehicles was calculated from GPS data received by Ford28. The distances are color-coded based on the received signal strength indicator (RSSI) values for the packets received by Ford28.

By comparing the results of Test Scenario 4.1.4 with that of Test Scenario 4.1.3, the data taken over a 25 second run showed that the number of packets from GM26 that were not received by Ford28 is about 2 percent and there has been no noticeable degradation in communication performance due to high relative speed in this scenario. The results of this test showed that communication between the two vehicles is possible up to 600 m on both directions of travel even at relative speeds of about 140 mph.

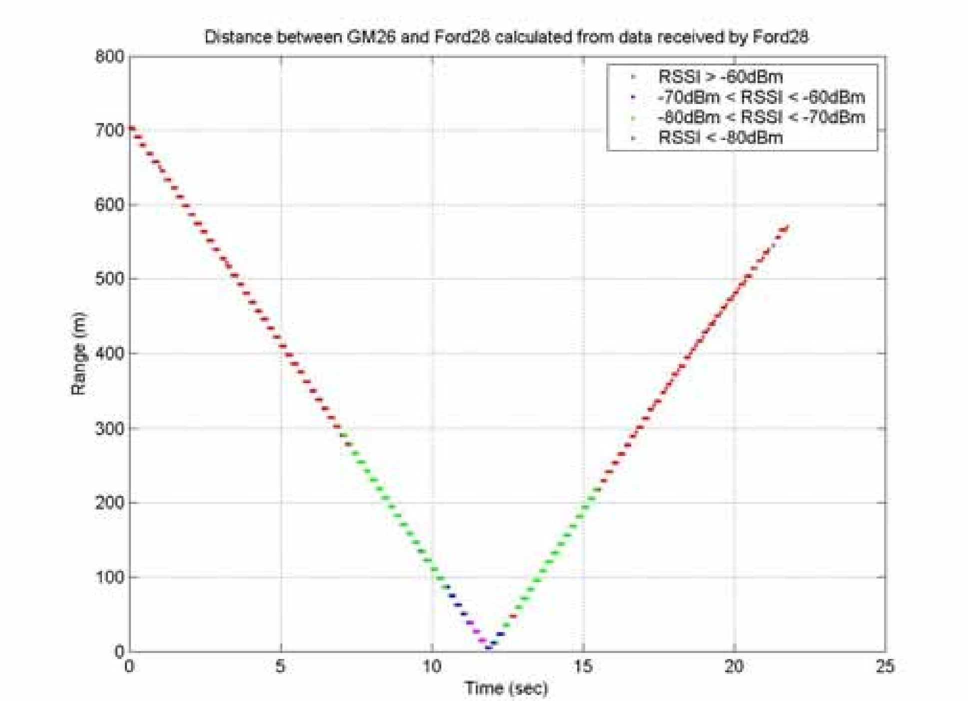



**Figure 106. Distance and RSSI Calculated from Data Received by Ford28**

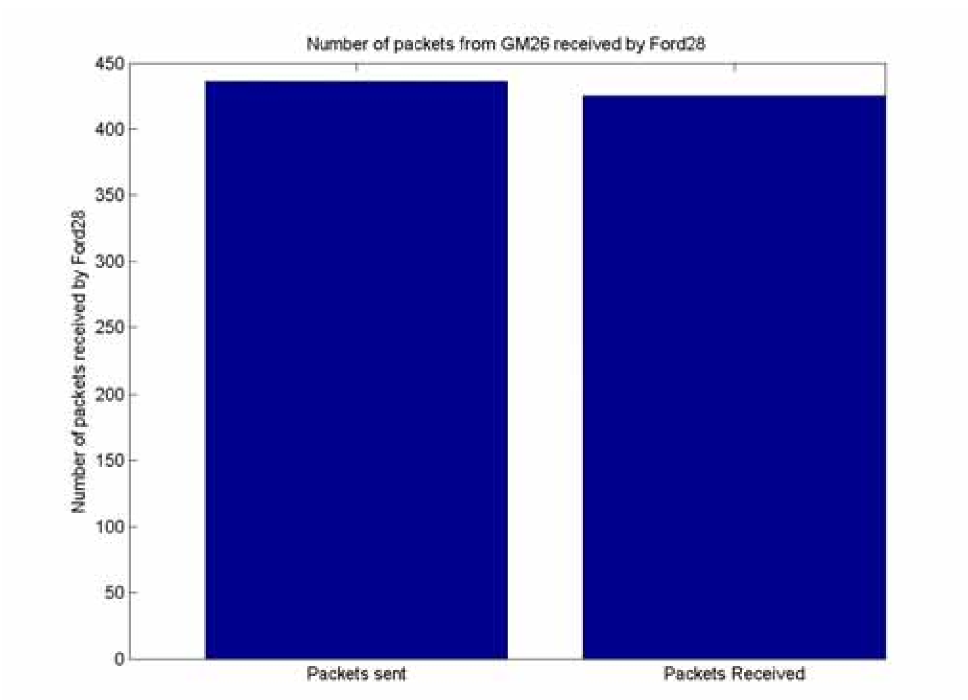



**Figure 107. Number of Packets from GM26 Received by Ford28**

### 4.1.5 Test for Communication Range Under Low Transmit Power

This test scenario is the same as in Figure 103. The WRM Transmit Power for this test has been reduced to 5 dBm in comparison to the Test Scenario 4.1.3 in which the Transmit power was set to full (~20 dBm). The other parameters for this test are shown in Table 16.

This test was used to determine the reduction in communication range under low Transmit Power conditions for vehicle-to-vehicle. The WRMs on both vehicles were configured to both send and receive data. The results of this test scenario are shown in Figure 108 and 109. The distance between the vehicles was calculated from GPS data received by Ford28. The distances are color-coded based on the received signal strength indicator (RSSI) values for the packets received by Ford28.

By comparing the results of Test Scenario 4.1.5 with that of Test Scenario 4.1.3, the data taken from a 50 second run showed that the number of packets from GM26 that were not received by Ford28 is greater than 10 percent. The communication range is about 250 m on each direction of travel, which is less that 50 percent of that obtained in Test Scenario 1.1.3 with a Transmit power of about 20 dBm. Nevertheless, the results of this test showed that, even with 5 dBm Transmit Power, vehicle-to-vehicle communication is possible between the two vehicles up to ranges of about 250 m on both directions of travel under test track conditions.

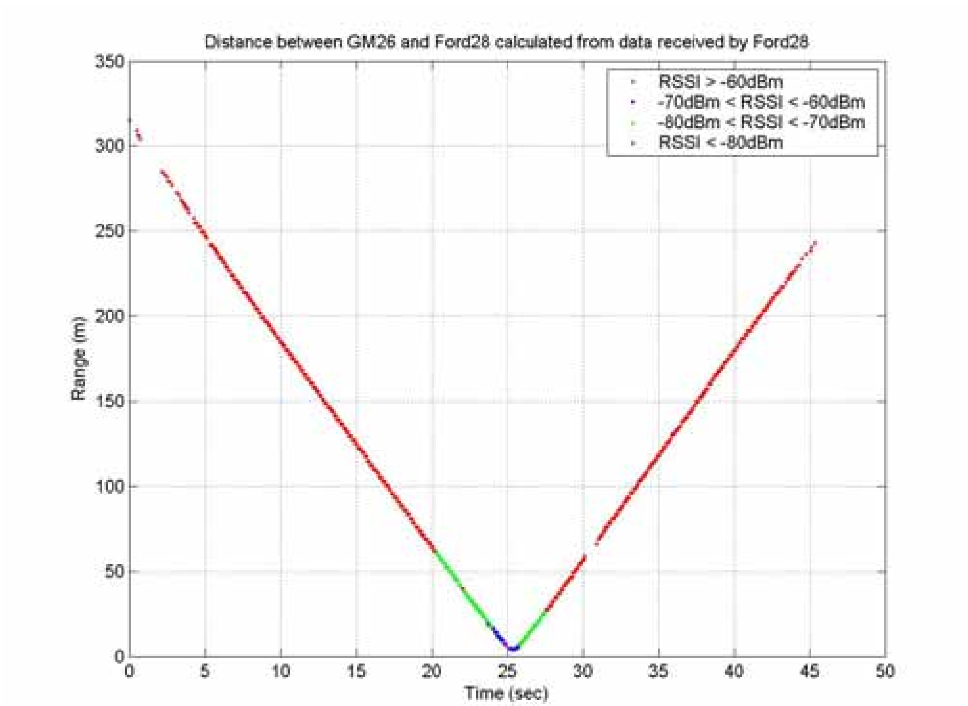



**Figure 108. Distance and RSSI Calculated from Data Received by Ford28**

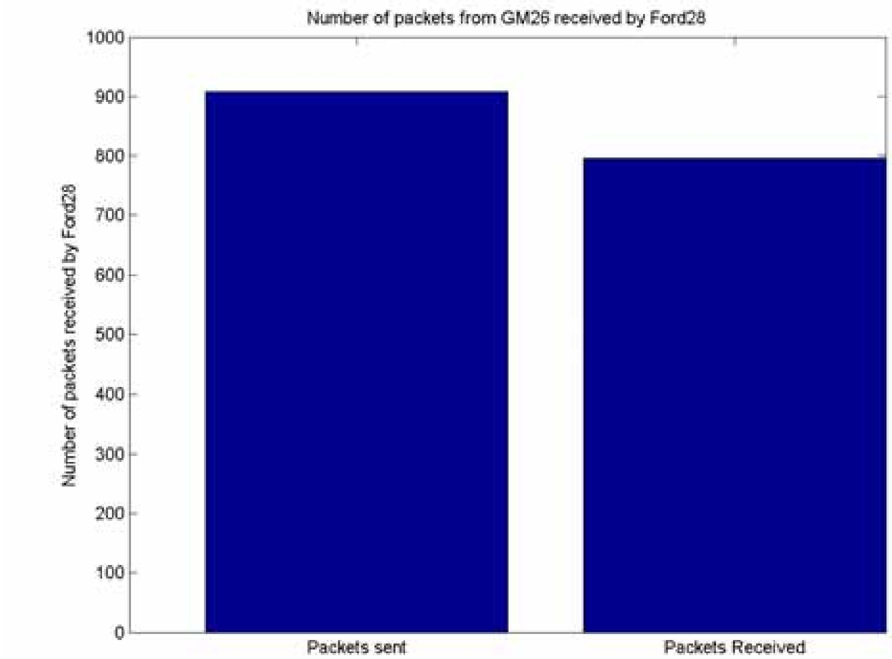



**Figure 109. Number of Packets from GM26 Received by Ford28**

### *4.1.6 Test for Communication Performance Under High Data Rate*

This test scenario is the same as in Figure 103. The WRM Data Rate for this test has been increased to 27 Mbps in comparison to the Test Scenario 4.1.3 in which the Data Rate was 6 Mbps. The other parameters for this test are shown in Table 16.

This test was used to determine the degradation in communication performance under high Data Rate transmissions for vehicle-to-vehicle. The IEEE stipulates that when the data rate is increased, the transmit power from the 802.11a chipset should be reduced (a 3-4 dBm reduction in these tests) in order to maintain transmitter quality and address the packet error rate. The WRMs on both vehicles were configured to both send and receive data. The results of this test scenario are shown in Figures 110 and 111. The distance between the vehicles was calculated from GPS data received by Ford28. The distances are color-coded based on the received signal strength indicator (RSSI) values for the packets received by Ford28.

By comparing the results of Test Scenario 4.1.6 with that of Test Scenario 4.1.3, the data taken over a 35 second run showed that the number of packets from GM26 that were not received by Ford28 is greater than 15 percent packet loss. The communication range is about 200 m on each direction of travel, which is less than 35 percent of that obtained in Test Scenario 4.1.3 with a Data Rate of 6 Mbps. The results of this test suggests that, in order to have better vehicle-to-vehicle communication between the two vehicles for vehicle safety applications, the minimum DSRC Data Rate of 6 Mbps should be used, since higher Date Rates are associated with higher packet losses and reduction in communication range for the same Transmit Power setting.

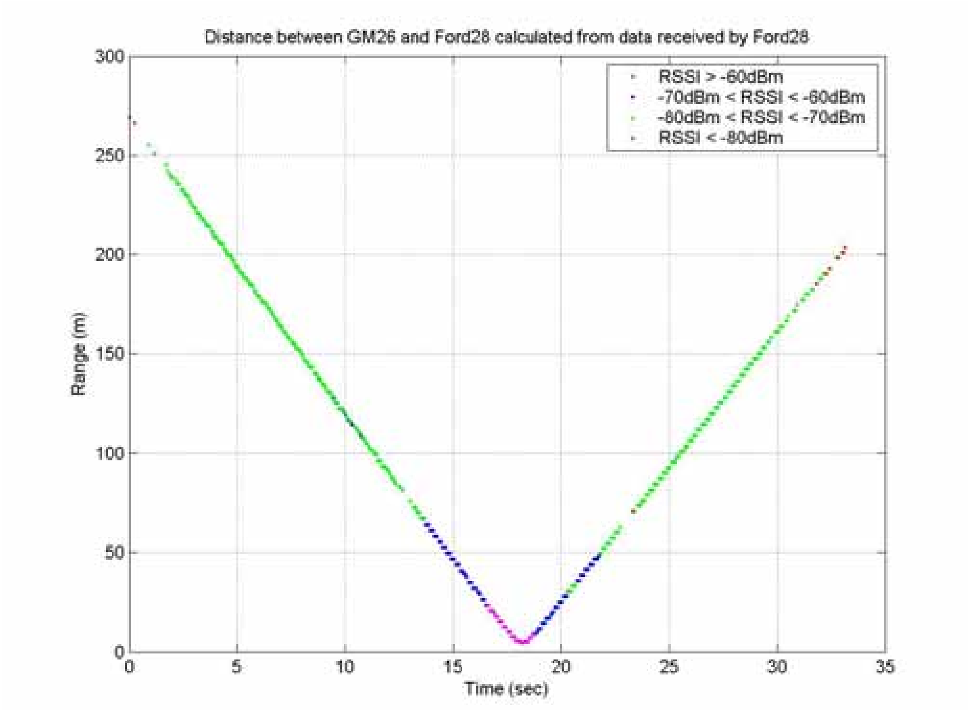



**Figure 110. Distance and RSSI Calculated from Data Received by Ford28**

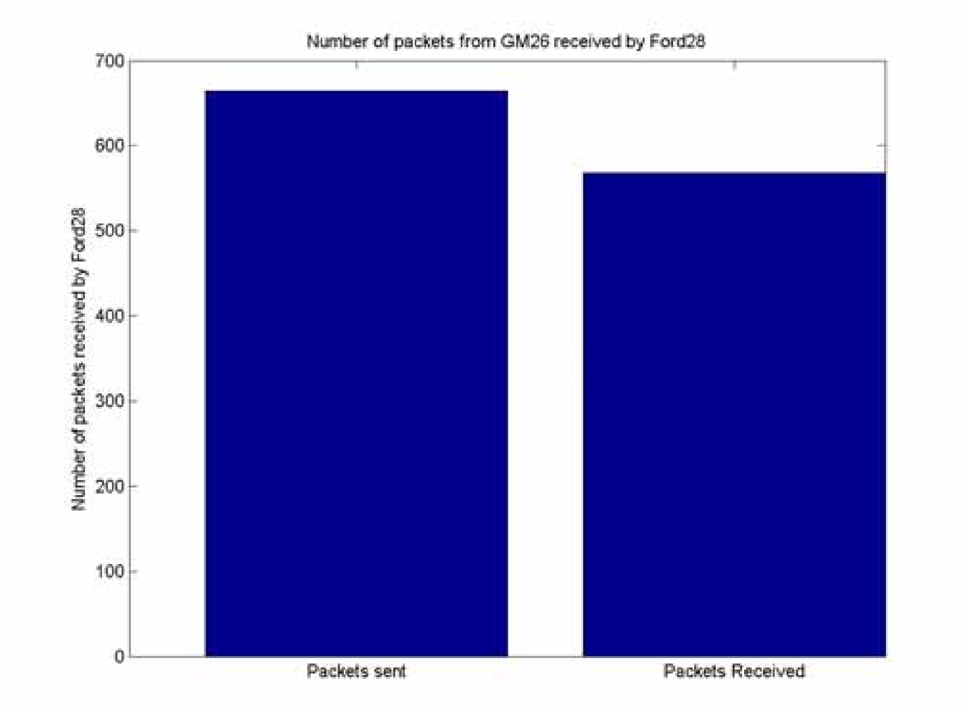



**Figure 111. Number of Packets from GM26 Received by Ford28**

## 4.2 Vehicle-to-Vehicle Communications Performance on I-96 Freeway and M-5 Ramp

Vehicle-to-vehicle communications testing was conducted on the I-96 freeway and M-5 ramp in Michigan in order to evaluate the communications performance on freeways. Seven vehicles – GM26, Nissan24, Toyota29, GM23, Ford25, Ford17 and Ford28, formed a caravan as shown in Figure 112. The caravan consisted of 4 sedans, 2 SUVs and a minivan. All seven vehicles were equipped with a DGPS Max receiver and antenna, WRM, and the Task 9 application running on a Laptop. The vehicle position information was obtained from the DGPS Max receiver that was configured to obtain differential corrections from the US Coast Guard beacons. One roof mount DSRC antenna (developed under the VSC Task 6C project) was used on the vehicles.

Three of these vehicles, Ford28 (Jaguar XKR developed by Ford for the EDMap project), GM23 and GM26 (both Buick Lesabres developed by GM for the ACAS project), had software modifications carried out so that they provided the vehicle signals over the CAN interface as defined in the Task 9 application. In all these tests, the WRMs were configured to send and receive on the DSRC Control Channel, which is Channel 178 with a center frequency of 5890 MHz and a 10 MHz bandwidth.


**Figure 112. Seven Vehicle Caravan**

### *4.2.1 Test Conducted on I-96 West*

This test scenario was conducted on the I-96 west freeway close to CAMP. The parameters for this test are shown in Table 17.

| *Packet Length (bytes)* | *Message Interval (ms)* | *Data Rate (Mbps)* | *Transmit Power (dBm)* |
|---|---|---|---|
| *200* | *100* | *6* | *Full (~20 dBm)* |

**Table 17. Parameters for Test Scenario No. 4.2.1**

As shown in Figure 112, GM26 is the lead vehicle followed by Nissan24, Toyota29, GM23, Ford25, Ford17 and Ford28 respectively. The caravan was made up of 4 sedans, 2 SUVs and a minivan. The WRMs on all vehicles were configured to both send and receive data. The results for a small segment of this test scenario are shown in Figure 113 through Figure 118. Distances between Ford28 and other vehicles were calculated from V-V communication received by Ford28. The distances are color-coded based on the received signal strength indicator (RSSI) values for the packets received by Ford28.

Since three of the seven vehicles have been developed to provide vehicle signal data over the CAN interface to the Task 9 application, their communication packets include actual vehicle signal data. Figure 114 shows the speeds for a small segment of this test scenario, color-coded based on the brake status, of GM26 and GM23 using data received by Ford28. Figure 115, Figure 116, and Figure 117 show the yaw-rate, longitudinal acceleration and lateral acceleration respectively of GM26 and GM23 for a small segment of this test scenario based on data received by Ford28.

The data from Figure 118 taken over a 300 second segment of this test scenario shows that out of 3000 packets sent by each vehicle, the number of packets received by Ford28 from GM26 is 2126 (71%), the number of packets received by Ford28 from Nissan24 is 2700 (90%), the number of packets received by Ford28 from Toyota29 is 2836 (95%), the number of packets received by Ford28 from GM23 is 2756 (92%), the number of packets received by Ford28 from Ford25 is 2384 (80%), and the number of packets received by Ford28 from Ford17 is 2997 (99.9%). The packet reception from GM26 was low because there were 5 vehicles between GM26 and Ford28, two of which were sedans, 2 were SUVs and one was a minivan. Thus the line of sight may have been obstructed and the distance between them was also large for much of the test duration. The packet reception from Ford25 was low due to the luggage roof rack of the minivan, which was obstructing the antenna pattern from the roof mount antenna used on that vehicle. This shows that the communication characteristics of the 5.9 GHz DSRC roof-mount antenna can be degraded by the luggage roof rack. In general, the results of this test show that, on the freeway environment, we have vehicle-to-vehicle communication between the vehicles to 180 m range with Transmit Power of 20 dBm.

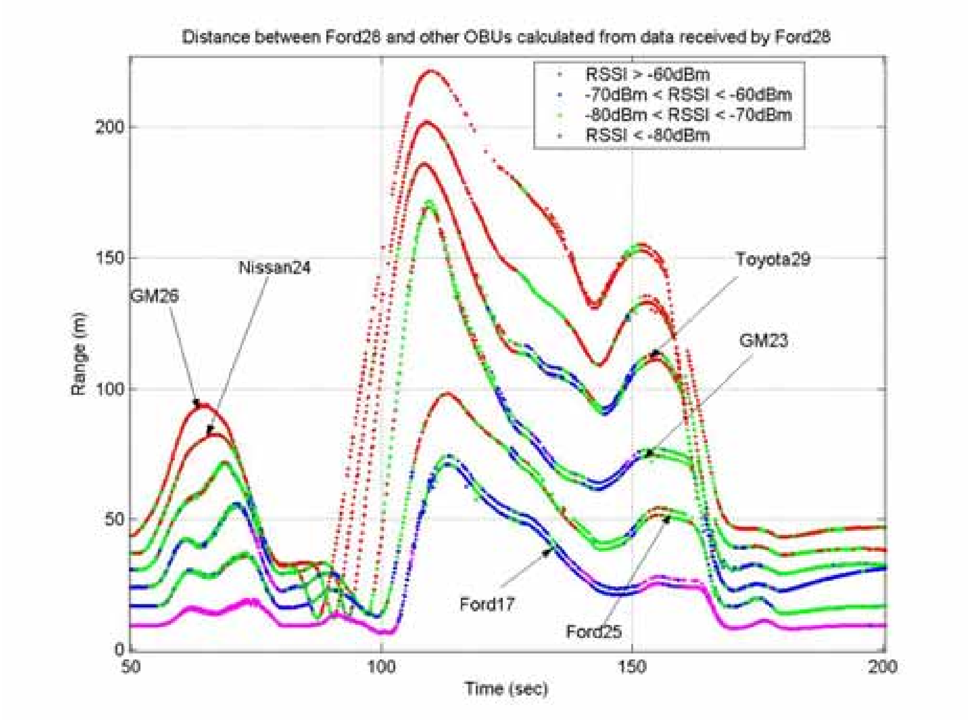



**Figure 113. Distances Calculated from Data Received by Ford28**

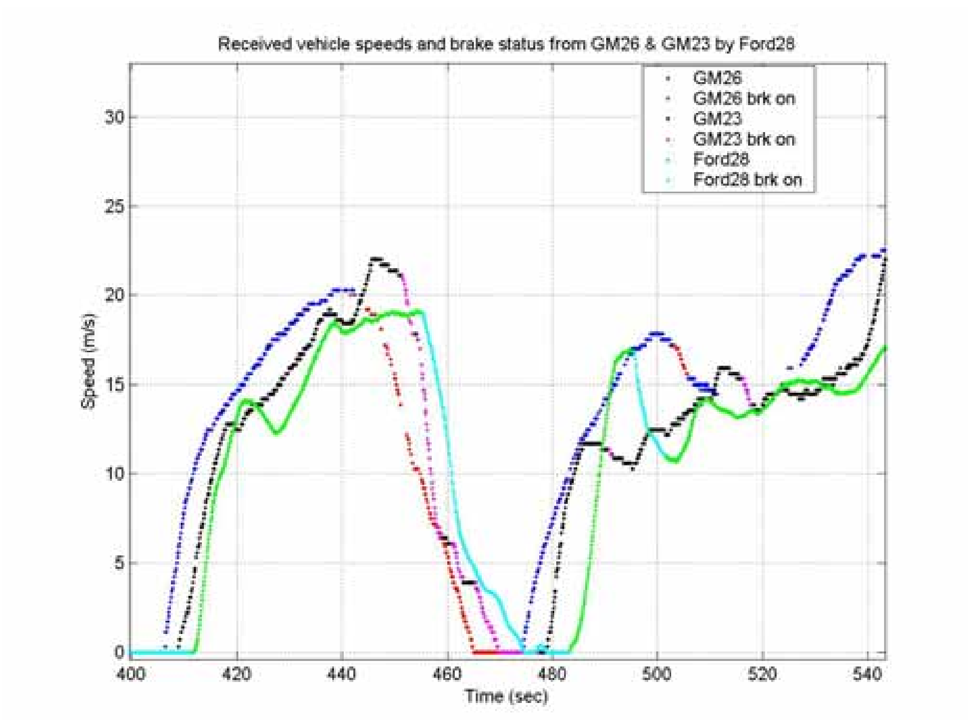



**Figure 114. Speed and Brake Status Received by Ford28**

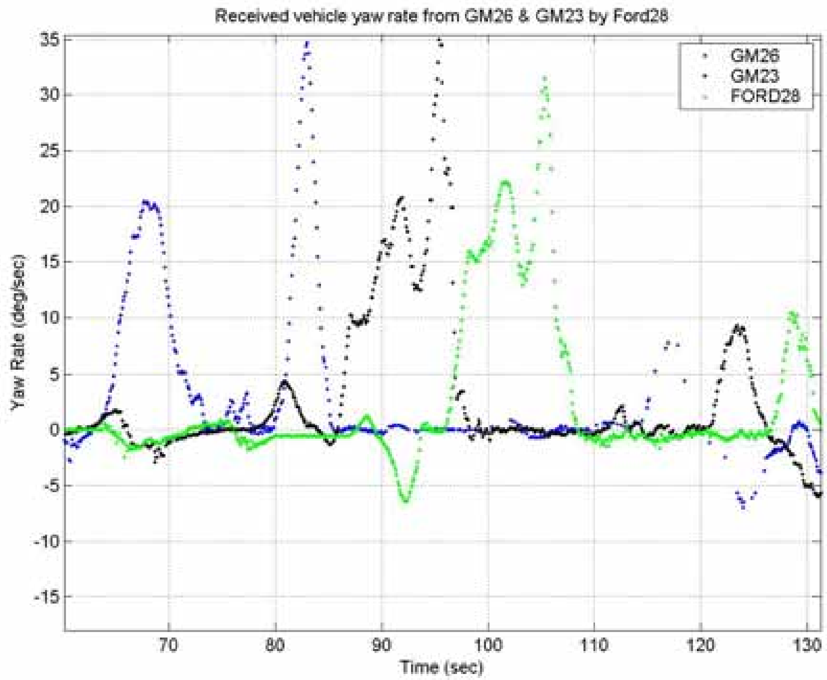



**Figure 115. Yaw Rate Received by Ford28**

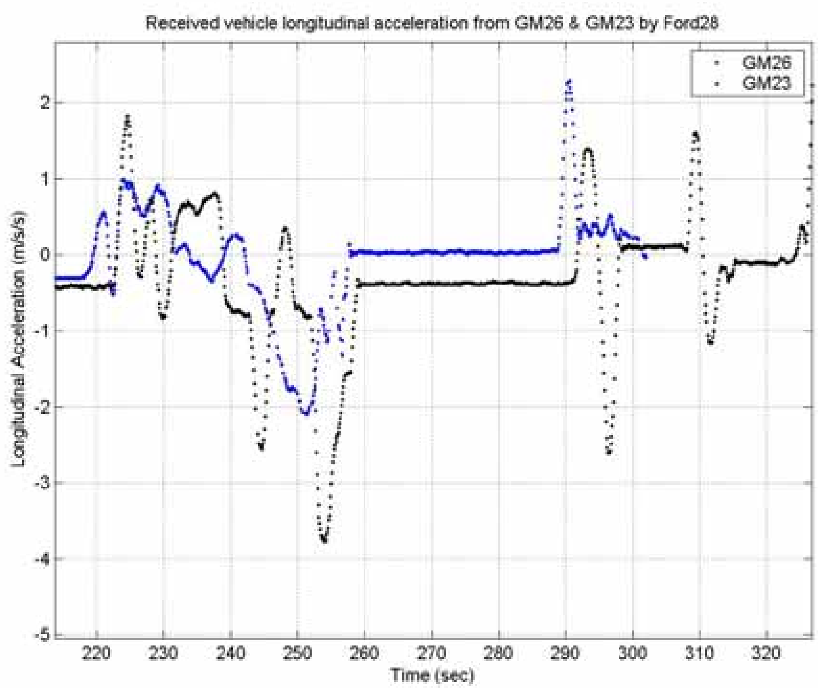



**Figure 116. Longitudinal Acceleration Received by Ford28**

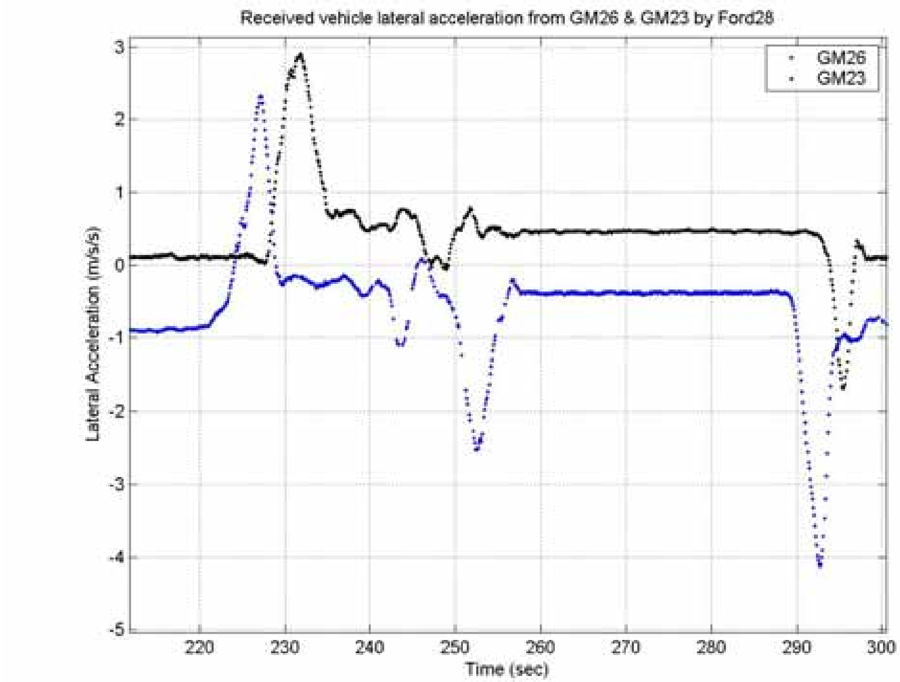



**Figure 117. Lateral Acceleration of Received by Ford28**

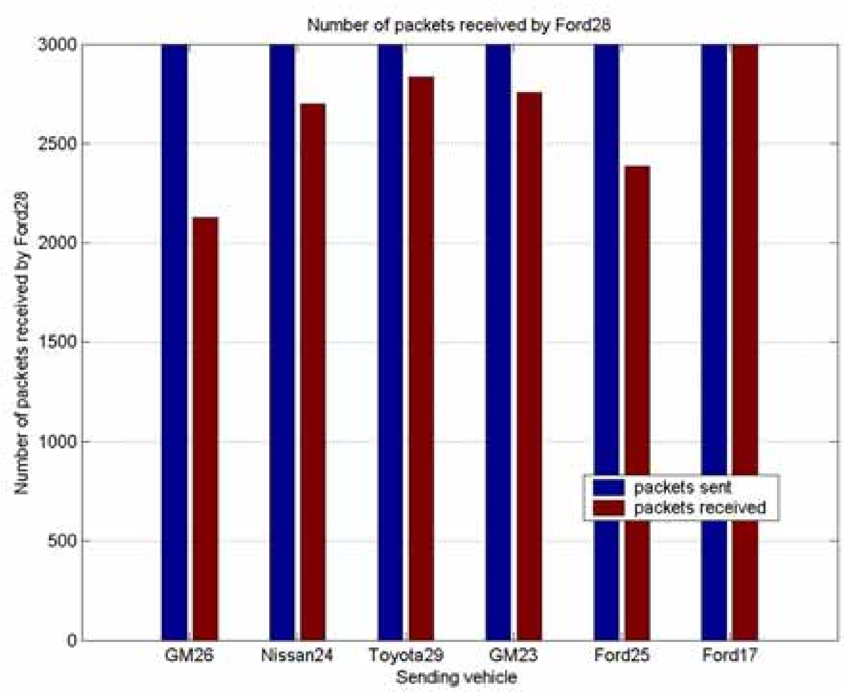



**Figure 118. Number of Packets from Other Vehicles Received by Ford28**

### *4.2.2 Test Conducted on I-96 East*

This test scenario was conducted on the I-96 east freeway close to Kensington Road in Michigan. The parameters for this test are shown in Table 18. In this test, the Transmit Power was reduced to 16 dBm.

| *Packet Length (bytes)* | *Message Interval (ms)* | *Data Rate (Mbps)* | *Transmit Power (dBm)* |
|---|---|---|---|
| *200* | *100* | *6* | *16* |

**Table 18. Parameters for Test No. 4.2.2**

As shown in Figure 112, GM26 is the lead vehicle followed by Nissan24, Toyota29, GM23, Ford25, Ford17 and Ford28 respectively. The WRMs on all vehicles were configured to both send and receive data. The results for a small segment of this test scenario are shown in Figure 119 through 124. Distances between Ford28 and other vehicles were calculated from V-V communication received by Ford28. The distances are color-coded based on the received signal strength indicator (RSSI) values for the packets received by Ford28. Figure 120 shows the speeds for a small segment of this test scenario, color-coded based on the brake status, of GM26 and GM23 using data received by Ford28. Figures 121 through 123 show the yaw-rate, longitudinal acceleration and lateral acceleration respectively of GM26 and GM23 for a small segment of this test scenario based on data received by Ford28.

The data from Figure 124 taken over a 600 second segment of this test scenario shows that out of 6000 packets sent by each vehicle, the number of packets received by Ford28 from GM26 is 2957 (49%), the number of packets received by Ford28 from Nissan24 is 4543 (76%), the number of packets received by Ford28 from Toyota29 is 5124 (85%), the number of packets received by Ford28 from GM23 is 5324 (89%), the number of packets received by Ford28 from Ford25 is 4754 (79%), and the number of packets received by Ford28 from Ford17 is 5995 (99.9%). By comparing these results with that of Test Scenario 4.2.1, we find that the packet reception from GM26 is much lower in this test because the Transmit Power used for this test was reduced to 16 dBm. We also find that the packet reception from Nissan24 and Toyota29 are much lower in this test because of the lower Transmit Power used. Again, the packet reception from Ford25 was low due to the luggage roof rack of the minivan, which was obstructing the antenna pattern from the roof mount antenna used on that vehicle. In general, the results of this test showed that, on the freeway environment, vehicle-to-vehicle communication were possible between the vehicles to 150 m range with reduced Transmit Power of 16 dBm.

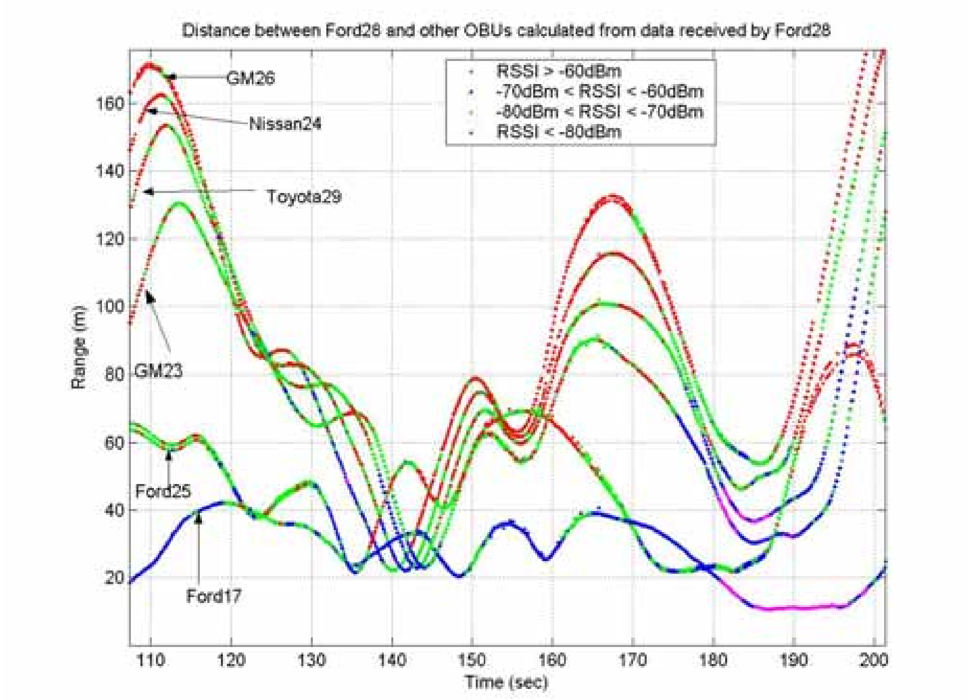



**Figure 119. Distances Calculated from Data Received by Ford28**

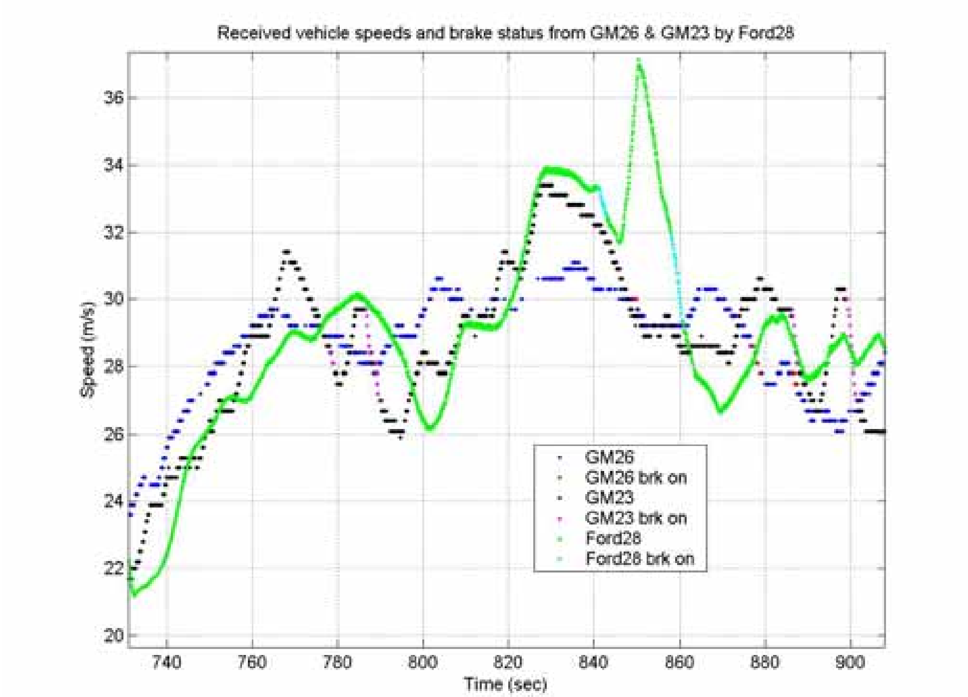



**Figure 120. Speed and Brake Status Received by Ford28**

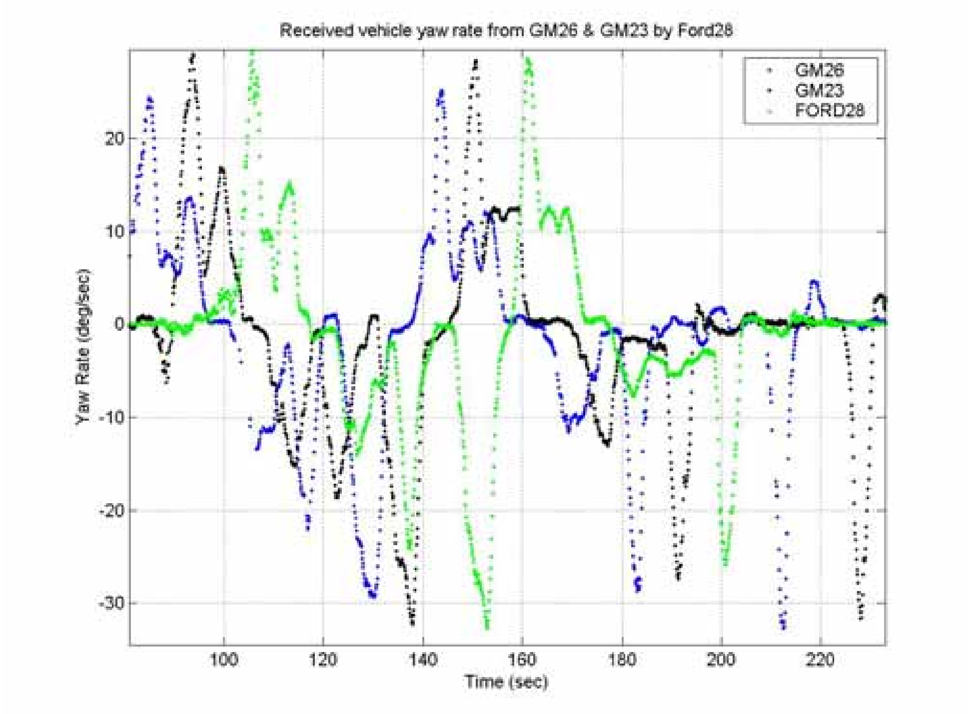



**Figure 121. Yaw Rate Received by Ford28**

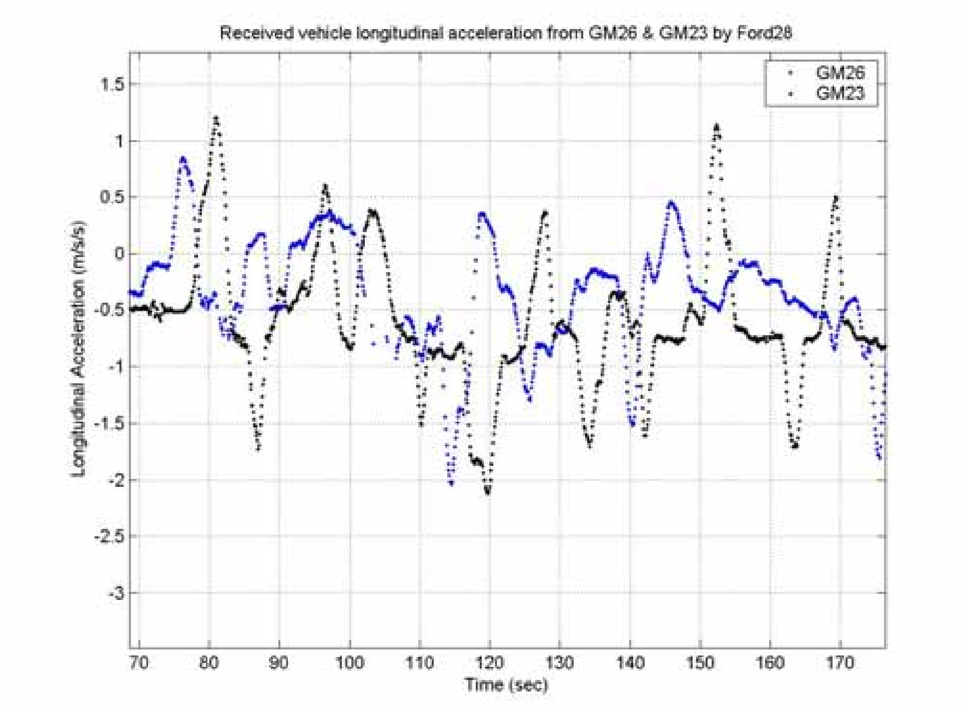



**Figure 122. Longitudinal Acceleration Received by Ford28**

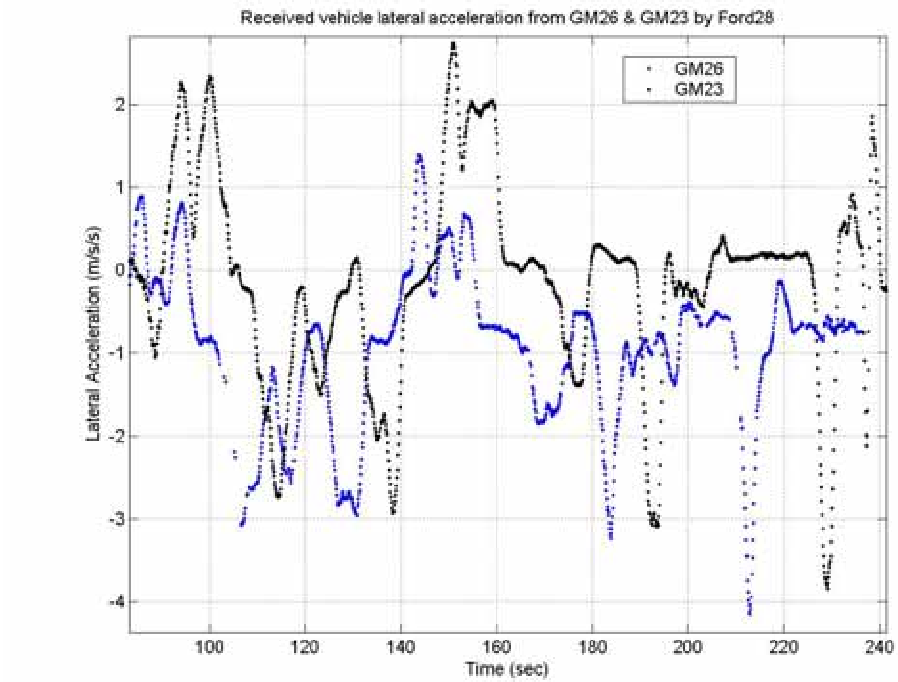



**Figure 123. Lateral Acceleration of Received by Ford28**

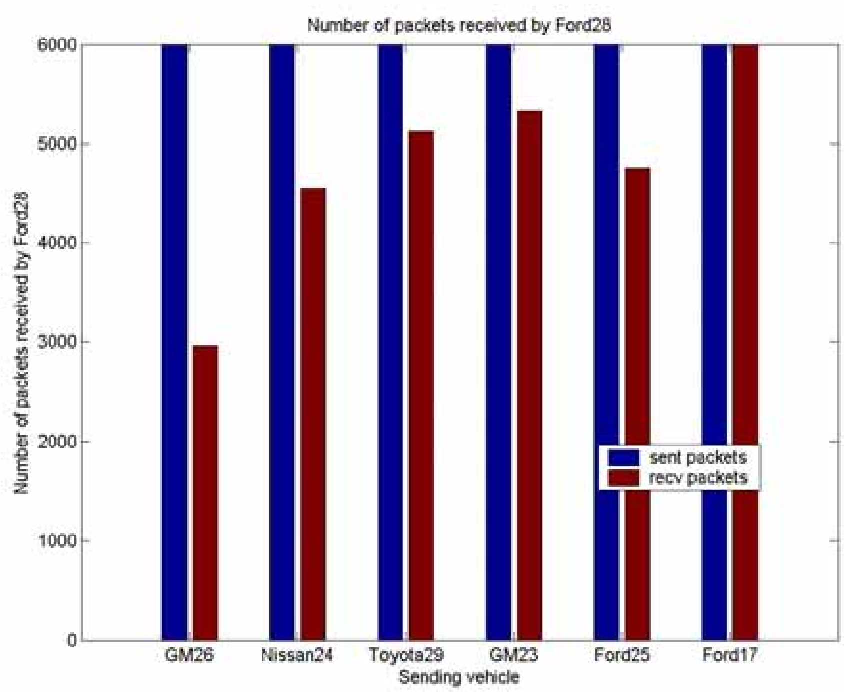



**Figure 124. Number of Packets from Other Vehicles Received by Ford28**

### *4.2.3 Test Conducted on M-5 Ramp to 12 Mile Road*

This test scenario was conducted on the M-5 ramp exit to 12 Mile Road in Michigan. The parameters for this test are shown in Table 19. In this test, the Transmit Power was set to 16 dBm.

| *Packet Length (bytes)* | *Message Interval (ms)* | *Data Rate (Mbps)* | *Transmit Power (dBm)* |
|---|---|---|---|
| *200* | *100* | *6* | *16* |

**Table 19. Parameters for Test Scenario No. 4.2.3**

As shown in Figure 112, GM26 is the lead vehicle followed by Nissan24, Toyota29, GM23, Ford25, Ford17 and Ford28 respectively. The WRMs on all vehicles were configured to both send and receive data. The results for this test are shown in Figures 125 through 130. Distances between Ford28 and other vehicles were calculated from V-V communication received by Ford28. The distances are color-coded based on the received signal strength indicator (RSSI) values for the packets received by Ford28. Figure 126 shows the speeds, color-coded based on the brake status, of GM26 and GM23 using data received by Ford28. Figures 125, 126, and 127 show the yaw-rate, longitudinal acceleration and lateral acceleration respectively of GM26 and GM23 based on data received by Ford28.

The data from Figure 130 taken over a 60 second segment of this test scenario shows that out of 600 packets sent by each vehicle, the number of packets received by Ford28 from GM26 is 565 (94%), the number of packets received by Ford28 from Nissan24 is 587 (98%), the number of packets received by Ford28 from Toyota29 is 596 (99%), the number of packets received by Ford28 from GM23 is 597 (99.5%), the number of packets received by Ford28 from Ford25 is 593 (99%), and the number of packets received by Ford28 from Ford17 is 600 (100%). In general, the results of this test showed that, on the freeway ramp environment, vehicle-to-vehicle communication were possible between the vehicles to 100 m range with reduced Transmit Power of 16 dBm.

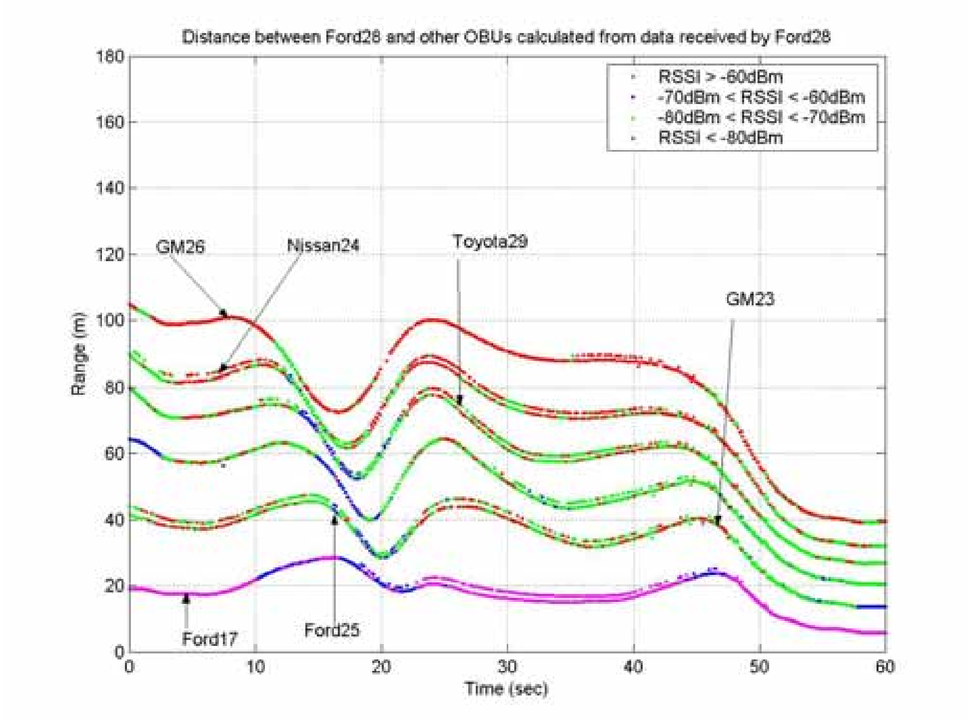



**Figure 125. Distances Calculated from Data Received by Ford28**

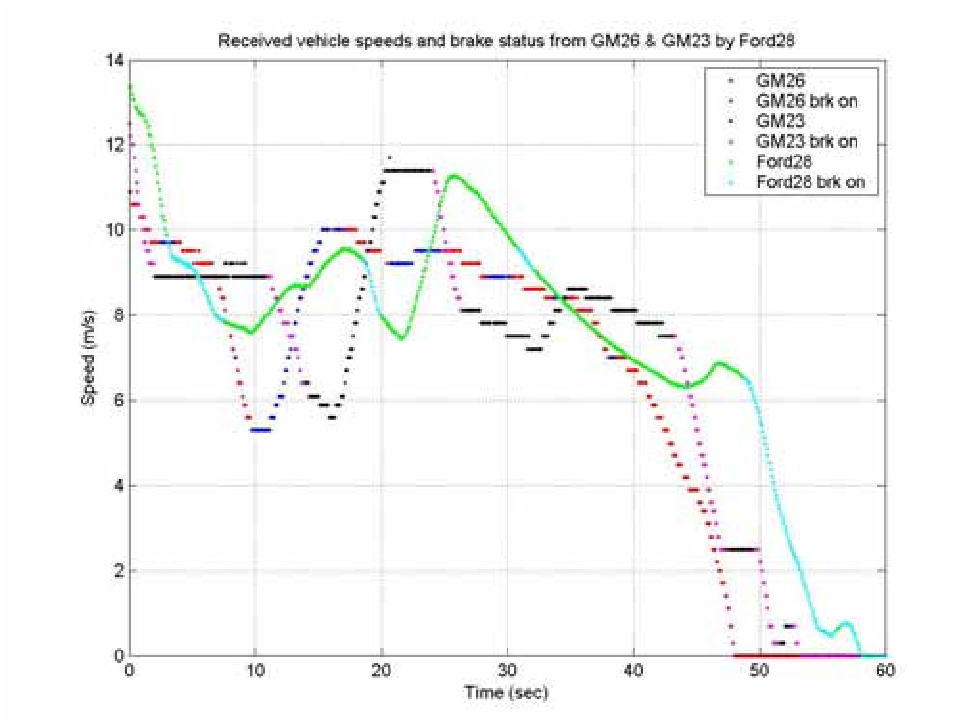



**Figure 126. Speed and Brake Status Received by Ford28**

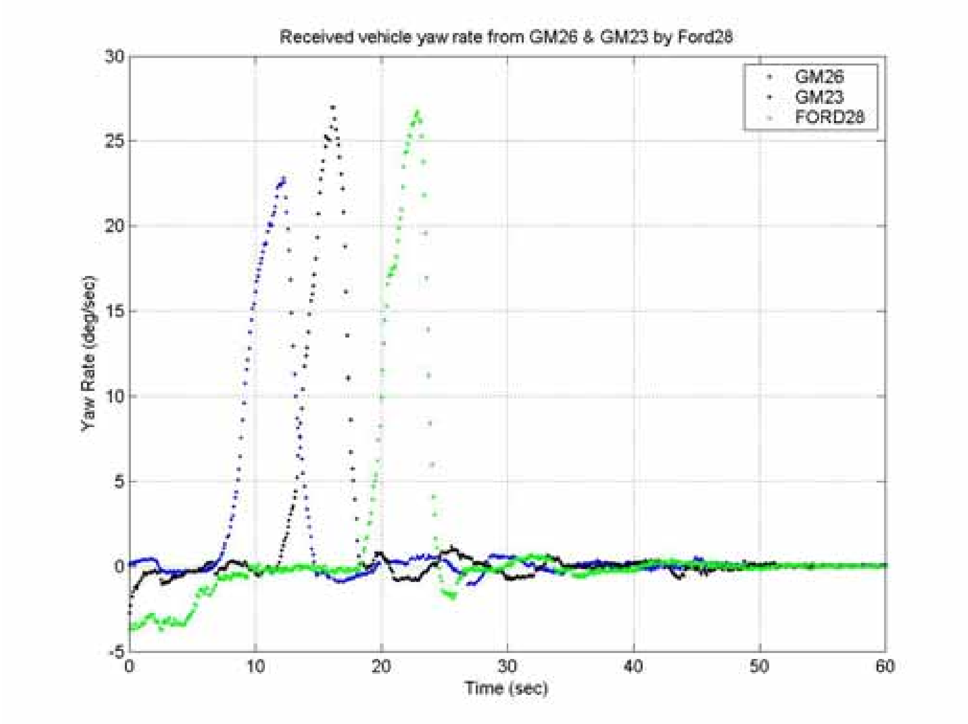



**Figure 127. Yaw Rate Received by Ford28**

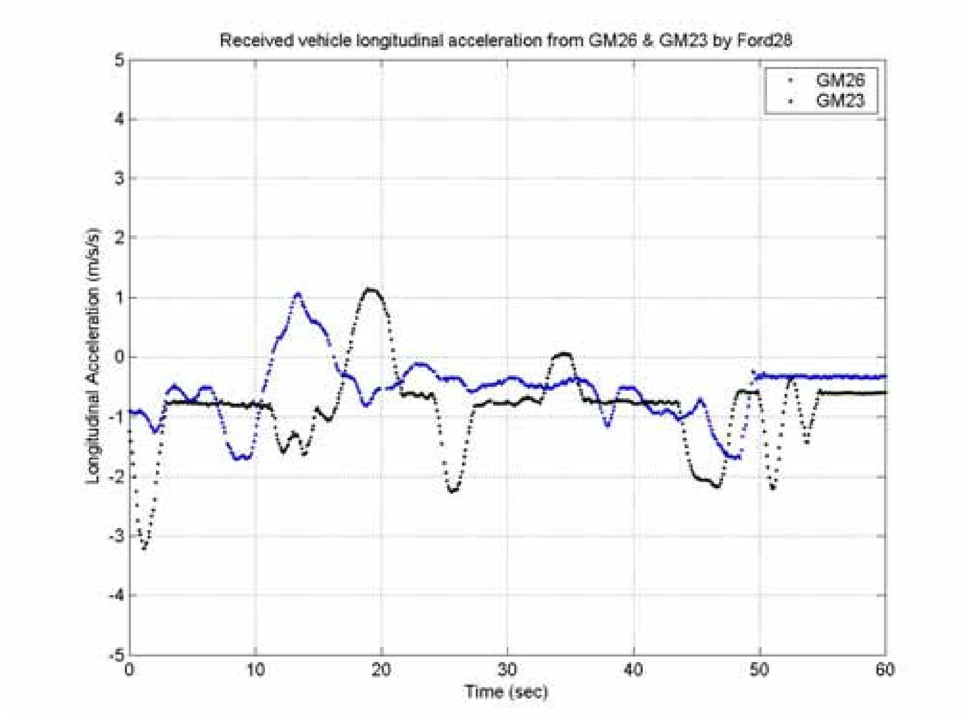



**Figure 128. Longitudinal Acceleration Received by Ford28**

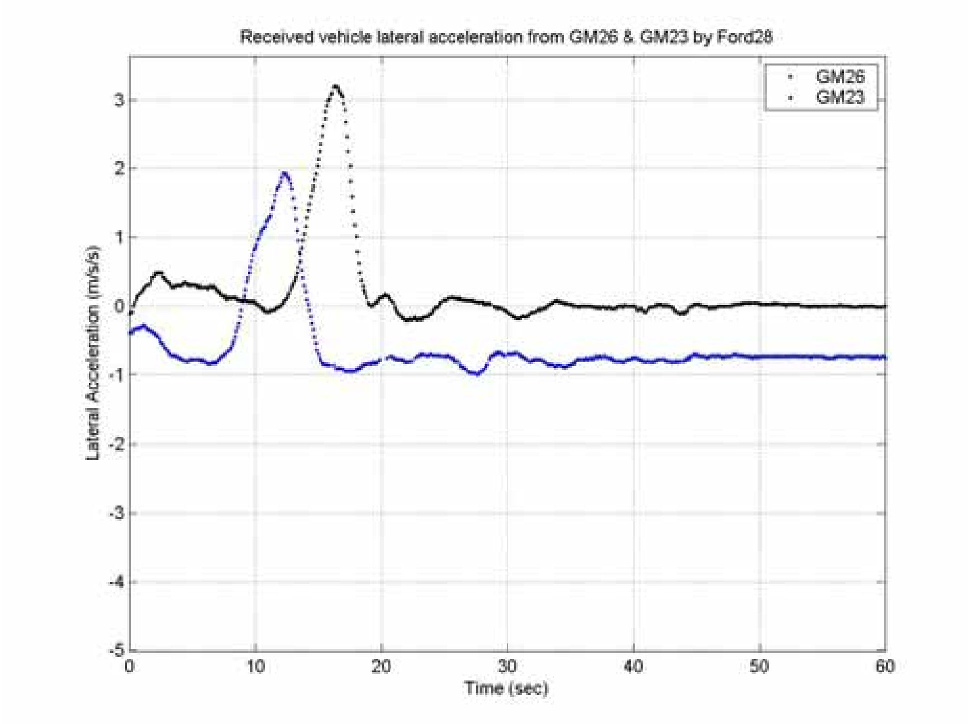



**Figure 129. Lateral Acceleration of Received by Ford28**

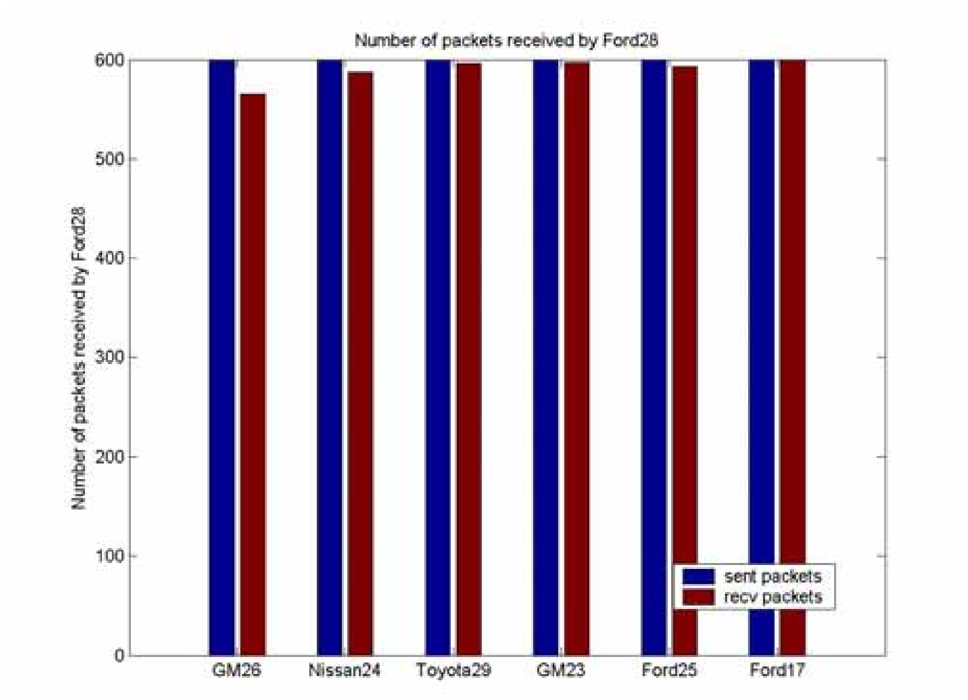



**Figure 130. Number of Packets from Other Vehicles Received by Ford28**

## 4.3 Summary

This section presented the results of the vehicle-to-vehicle communications testing conducted at the Milford Proving Grounds (MPG), I-96 freeway, and the M-5 ramp in Michigan to evaluate the performance of the Wave Radio Modules (WRMs) under vehicle-to-vehicle communications scenarios. In all the tests, the WRMs were configured to send and receive on the DSRC Control Channel, which is Channel 178 with a center frequency of 5890 MHz and a 10 MHz bandwidth.

The vehicle-to-vehicle communications testing at MPG was conducted using a Jaguar XKR developed by Ford for the EDMap project, and a Buick Lesabre developed by GM for the ACAS project. Software modifications were carried out on both these vehicles so that they provide the vehicle signals over the CAN interface as defined in the Task 9 application. Based on the V-V communications testing at MPG the following conclusions can be made:

- Results showed true omni-directional characteristics of the 5.9 GHz DSRC roof-mount antenna developed under Task 6 of the VSC project.
- Results showed 100 percent reception and no packet loss with vehicle-to-vehicle communication between the two vehicles up to ranges that exceeded 200 m in a vehicle following scenario.
- Results show that we have vehicle-to-vehicle communication between the two vehicles up to ranges that exceed 600 m on both directions of travel.
- Results showed that reducing the transmit power from 20 dBm to 5 dBm reduced the range of vehicle-to-vehicle communication to about 250 m on both directions of travel.
- Results showed that increasing the data rate from 6 Mbps to 27 Mbps was associated with higher packet losses and reduction in communication range, as expected, due to the subsequent reduction in transmit power (3-4 dBm) that takes place based on IEEE stipulations.

Vehicle-to-vehicle communications testing was conducted on the I-96 freeway and M-5 ramp in Michigan in order to evaluate the communications performance on freeways. Seven vehicles – GM26, Nissan24, Toyota29, GM23, Ford25, Ford17 and Ford28, formed a caravan as shown in Figure 112. The caravan consisted of 4 sedans, 2 SUVs and a minivan. Three of these vehicles, Ford28 (Jaguar XKR developed by Ford for the EDMap project), GM23 and GM26 (both Buick Lesabres developed by GM for the ACAS project), had software modifications carried out so that they provide the vehicle signals over the CAN interface as defined in the Task 9 application. Based on the V-V communications testing on freeways the following conclusions can be made:

- In general, the results showed that, on the freeway environment, vehicle-to-vehicle communication were possible between the vehicles to 180 m range with Transmit Power of 20 dBm.

- Results showed that the communication characteristics of the 5.9 GHz DSRC roof-mount antenna can be degraded by the luggage roof rack.

- Results showed that the packet reception can be affected because of line of sight obstructions from SUVs and minivans.

- Results showed that reducing the Transmit Power from 20 dBm to 16 dBm reduced the range of vehicle-to-vehicle communication between the vehicles to 150 m. Also the packet reception because of line of sight obstructions from SUVs and minivans can be affected severely by reduction in Transmit Power.

- In general, the results of this test showed that, on the freeway ramp environment, vehicle-to-vehicle communications were possible between the vehicles to 100 m range with reduced Transmit Power of 16 dBm.

Based on the V-V testing conducted, the communication characteristics and performance of the WRMs are promising for vehicle safety application development in the future.